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(12) **EUROPEAN PATENT APPLICATION**

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(54) Flow control system.

(57) A flow control system for use in a compressible fluid fuelled internal combustion engine includes a pressure regulator (14) for reducing the prezsure of a fuel stored at a first pressure to a lower second pressure suitable for metering. The regulator includes a regulating valve controlling communication between an inlet fluid manifold and a regulated fluid manifold and is arranged to produce a drop in pressure of the flowing fluid through the valve to the second pressure. The regulator further includes a relief valve (36) arranged to open to exhaust fluid when the pressure in the regulated fluid manifold rises above a predetermined level. The regulator is also provided with heating means (34) for heating the regulator body to compensate, to some degree at least, for the drop in temperature in the fluid as the fluid expands on passing through the regulating valve. There is further provided a fluid metering device (16) comprising a plurality of fluid lines for communication between an inlet fluid manifold and a metered fluid manifold. Bi-stable valves of various orifice sizes are provided, one in each of the fluid lines. The device also includes sensors for determining parameters of the inlet fluid sufficient to determine potential mass flow of fluid through each of the valves; and valve controls for activating valve actuators to open the valves in combinations and for time intervals to give a desired total mass flow of fluid through the valves. The total fluid flow passing from the metering device comprises a base flow component established by opening selected control valves to provide a continuous predetermined flow, discrete step changes in the base flow component being provided by opening and closing combinations of control valves. Increments of fluid flow between the discrete steps are provided by opening at least one pulsing valve for a fraction of a predetermined time period to provide a desired average flow over the time period.

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FLOW CONTROL SYSTEM

This invention relates to the control of the flow rate of a fluid, and in particular to the control of the supply of compressible fluid fuels for internal combustion engines.

5 BACKGROUND OF THE INVENTION

Systems for converting conventional gasoline and diesel fuel led internal combustion engines to run on compressible fluid fuels, such as natural gas and propane, have been available for some time. Under current fiscal policy, there is generally a considerable retail price advantage to using propane or natural gas
10 as a fuel, such that, for example, taxi operators and police forces can rapidly recoup the extra cost of providing a vehicle with the capability to run on propane or natural gas. Even without advantageous tax structuring the cost of a natural gas is generally lower than that of gasoline and diesel fuels, natural gas requiring relatively minor processing before it is in a saleable form, whereas conventional liquid gasoline fuels are often produced by "cracking" and processing of other longer chain hydrocarbons. Also, spark
15 ignition engines running on natural gas do not suffer from compression ignition or "knocking" (except at very high compression ratios and intake air temperatures on large bore engines), and thus, the need for the provision of natural gas with different characteristics, similar to octane rated gasoline, is obviated. This also removes the requirement to provide knock resisting additives, such as the lead based additives used in some gasoline. Further, the major component of natural gas is methane, a "clean" fuel, which produces
20 substantially less carbon dioxide on burning than does conventional gasoline or diesel fuel.

Despite these advantages the use of natural gas has met with only limited acceptance. This may be linked, in part at least, to a number of areas where natural gas powered vehicles compare unfavourably with conventional gasoline fuelled vehicles. The technology for utilizing natural gas fuel in this area is not as well developed as that used in conventional gasoline fuelling systems and existing products are generally
25 relatively expensive to produce, install and service. Also, the conversion of a gasoline engine to run on natural gas normally results in a decrease in power output and a corresponding drop in vehicle performance.

A typical gaseous fuel injection system includes a pressurized fuel storage tank, a pressure regulator for reducing the fuel from the relatively high storage pressure to a lower working pressure, a metering valve
30 for controlling the gas supply to the engine and a gas/air mixer at the engine air intake. Some form of engine management system is also provided to control the metering valve and ensure proper engine operation.

Pressure regulators in existing gaseous fuel injection systems tend to be bulky and thus are difficult to locate in the often restricted space of a vehicle engine compartment. Accordingly, these are often suitable
35 for use only on engines with spacious engine compartments. The bulk of existing regulators is due, in part at least, to the number of components which are present in a regulator: a fuel filter in the fuel line from the fuel storage tank; at least two regulating valve stages for reducing the pressure of the fuel as it passes through the regulator; a relief valve which opens in the event of a failure of the regulator valve to prevent high pressure fuel from passing unchecked through the regulator, and a heater to warm the regulator and
40 compensate for the cooling effect of expanding the fluid at the regulating valve.

Regulator fuel filters must be of rugged construction, since if they become blocked they may have to withstand high pressures (up to 4000 p.s.i. for natural gas), and a failure of the filter may result in considerable damage to the regulator and other components downstream of the valve.

Existing regulator valves permit relatively low flow rates, and are prone to blocking; in some cases, two
45 or three stage regulators must be provided to accomplish a desired pressure drop and stability. Further, increasing the flow through the regulating valve tends to lead to pressure "droop", that is, the pressure drop at the valve at high flow rates is proportionally greater than the pressure drop at lower flows, leading to difficulties in calibration.

Tests on relief valves provided in existing fuel injection systems indicate that the valves are not
50 particularly reliable and often will not open at the intended pressure. Further, some doubt has been expressed as to the ability of existing valves to accommodate the flow rates experienced on failure of the regular valve: if a relief valve on a regulator should fail, the regulator may be destroyed, in explosive fashion, by the build-up of internal fuel pressure.

Heating of regulators is normally accomplished using the engine cooling fluid, and is particularly important in natural gas fuelled vehicles, where the drop in pressure and temperature produced by the

regulator valve may result in the appearance of hydrates, a lattice of methane and water present in the fuel, which has the appearance of "spongy" ice and which will block most regulator valves.

The control of the flow of the fuel between the regulator and the engine is accomplished by the metering valve which may take the form of a plurality of injectors which are operated to provide a desired
5 fuel flow. The volume of gaseous fuel required for fuelling an engine normally necessitates provision of a number of injectors which must be capable of supplying fuel at the desired rates for idling up to maximum power, which may be a 1:40 range.

Conventional injection systems commonly utilize "multi-point" fuel injection systems in which at least one solenoid operated injector valve is provided for each engine cylinder. Sensors measure various engine
10 operating parameters and an engine control system equates the inputs from the sensors to a desired fuel supply which is metered by, for example, operating the injectors for timed intervals, or varying the pressure of the fuel supplied to the injectors.

In "single-point" fuel injection a metered mass of fuel is supplied to a common inlet manifold. A form of such fuel injection for use with compressible fuels such as methane and propane is disclosed in United
15 States Patent No. 4,487,187 to Petro, entitled "Electronically Controlled Fluid Flow Regulating System". The system is provided with a metering valve including a plurality of parallel lines, each of which contains a solenoid valve, operated in response to digital signals produced by an electronic digital processor. The valve orifice sizes, and the relative flow rates through the valves, are proportional to successive powers of two, and the fuel pressure differential in the system is maintained such that critical or choked flow is
20 maintained through the orifices.

In common with other binary valves of this form, such as the valve described in United States Patent No. RE 29,383 to Gallatin et al., the flow through the valve increases/decreases in small incremental steps, the relative size of the steps between minimum and maximum flow through the valve decreasing as the number of valves is increased. However, increasing the number of valves increases the bulk and expense of
25 the metering device.

Further, binary systems such as those disclosed in the Petro and Gallatin et al. patents have poorest flow resolution at low flowrates, which tend to be the most critical for engine operation. Vehicle engines must operate over a wide dynamic range of fuel flows, typically around 35:1. At any point in the fuel delivery range, a fuelling system should be capable of adjusting the fuel flow by 0.25%. In, for example, a
30 12-bit binary valve for providing a flowrate of 4096 Standard Cubic Feet per Hour (SCFH), that is, a binary valve having twelve valves which increase in flow capacities following a binary sequence, at the lowest point of the dynamic range, the minimum increment to the next flow point represents 0.85% of that flow. Thus, such systems would not be capable of controlling the fuel flow within the desired range (0.25%), and an engine equipped with this form of binary metering valve would operate inefficiently and have difficulty in
35 conforming with proposed emission regulations which require precise control of the fuel supply.

SUMMARY OF THE INVENTION

40 According to a first aspect of the present invention there is provided apparatus for controlling the rate of flow of a fluid from a common inlet to a common outlet. The apparatus comprises a plurality of fluid conducting lines having a plurality of flow capacities, the lines being connected in parallel between the common inlet and the common outlet such that the total flow from the common inlet to the common outlet is equal to the sum of the separate flows through the individual lines. The apparatus further includes bi-
45 stable fluid flow control valves located in each of the lines, at least one of the control valves being a pulsing valve, sensors for measuring parameters of the fluid sufficient to determine the potential mass flow through each control valve when open and control means adapted to control selectively the opening and closing of the control valves and monitor the sensors to determine the potential mass flow through each control valve in accordance with the measured fluid parameters. The total fluid flow passing outwardly of the common
50 outlet comprises a base flow component established by opening selected control valves to provide a continuous predetermined flow, discrete step changes in the base flow component being provided by opening and closing combinations of control valves, increments of fluid flow between the discrete steps being provided by opening at least one pulsing valve for a fraction of a predetermined time period to provide a desired average flow over the time period.

55 According to a second aspect of the present invention there is provided a method for controlling the rate of flow of a compressible fluid between a common inlet at a first pressure and a common outlet at a lower second pressure through a plurality of parallel fluid conducting lines adapted to provide a plurality of flowrates therethrough, each fluid conducting line being provided with a bi-stable fluid flow control valve, at

least one of the valves being a pulsing valve. The method comprises controlling selectively the opening and closing of the control valves to control the fluid flow passing outwardly of the common inlet by providing a base flow component established by opening selected control valves to provide a continuous predetermined flow, discrete step changes in the base flow component being provided by opening and closing combinations of control valves, increments of fluid flow between the discrete steps being provided by opening at least one pulsing valve for a fraction of a predetermined time period to provide a desired average flow over the predetermined time period.

According to a third aspect of the present invention there is provided a fluid metering device for use in a compressible fuel injection system for an internal combustion engine comprising a body defining an inlet fluid manifold and a metered fluid manifold, and a fluid inlet for passage of fluid into the inlet fluid manifold. The device includes a plurality of valves for controlling fluid communication between the inlet fluid manifold and the metered fluid manifold, the body further defining a fluid outlet for passage of metered fluid from the metered fluid manifold. Sensors are provided for determining parameters of the inlet fluid and the metered fluid sufficient to determine actual mass flow of fluid through each of the valves. A device operating system includes valve control means for activating the valve actuators to open the valves in combinations and for time intervals to give a desired total mass flow of fluid through the valves.

According to a fourth aspect of the present invention there is provided a pressure regulator for use in a gaseous fuelled internal combustion engine for reducing the pressure of a fuel stored at a first pressure to a lower second pressure suitable for metering comprising: a body defining an inlet fluid manifold and a regulated fluid manifold; a fluid inlet for passage of fluid at a first pressure into the inlet fluid manifold; a single stage regulating valve controlling fluid communication between the inlet fluid manifold and the regulated fluid manifold and arranged to produce a drop in pressure of the fluid through the valve to the lower second pressure; a relief valve in fluid communication with the regulated fluid manifold and arranged to open to exhaust fluid when the pressure in the regulated fluid manifold rises above a predetermined level; heating means for heating the body to compensate to some degree at least for the drop in temperature in the fluid as the fluid passes through the regulating valve; and a fluid outlet in communication with the regulated fluid manifold for passage of fluid from the manifold.

According to a fifth aspect of the present invention there is provided a method of mixing a metered supply of compressible fluid fuel with the intake air of an internal combustion engine comprising providing a source of metered fuel at a positive pressure and dispersing the fuel in the air intake of the engine through a diffuser cone.

According to a sixth aspect of the present invention there is provided a method of mixing a metered supply of compressible fluid fuel with the intake air of an internal combustion engine comprising providing a source of metered fuel at a positive pressure and dispersing the fuel in the air intake of the engine.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other aspects of the present invention will now be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a block diagram of a vehicle engine provided with a fuel supply system in accordance with a preferred embodiment of the present invention;

Figure 2 is a block diagram of a fuel pressure regulator of the fuel supply of Figure 1;

Figure 3a is a sectional view of a fuel pressure regulator of the fuel supply system of Figure 1, taken on line 3a-3a of Figure 3b;

Figure 3b is a bottom plan view of the fuel pressure regulator;

Figure 3c is an end elevational view of the fuel pressure regulator;

Figure 3d is a sectional view on line 3d-3d of Figure 3b and illustrating details of a fuel inlet;

Figure 3e is a sectional view on line 3e-3e of Figure 3b and illustrating details of a relief valve assembly;

Figure 4 is a block diagram of a fuel metering valve of the fuel supply system of Figure 1;

Figure 5a is a top plan view of the fuel metering valve of the fuel supply system of Figure 1;

Figure 5b is a side elevational view of the fuel metering valve;

Figure 5c is an end elevational view of the fuel metering valve;

Figure 5d is a pictorial view showing the top side of the metering valve electronic control board;

Figure 6 is a sectional view on line 6-6 of Figure 5a;

Figure 7a is a top plan view of the valve block of the fuel metering valve showing the hidden detail of the inlet manifolding;

Figure 7b is a top plan view of the valve block of the fuel metering valve showing the hidden detail of the

outlet manifolding;

Figure 7c is a top plan view of the valve block of the fuel metering valve showing the hidden detail of the coolant manifolding;

Figure 7d is a sectional view on line 7d-7d of Figure 7a.

Figure 8 is a sectional view of an engine air intake showing one example of an air/fuel mixer for use with the fuel supply system of Figure 1;

Figure 9 is a sectional view of an engine air intake showing a further example of an air/fuel mixer, in the form of a nozzle, for use with the fuel supply system of Figure 1; and

Figure 10 is a block view of the controller of the supply system of Figure 1.

DESCRIPTION OF PREFERRED EMBODIMENTS

Reference is first made to Figure 1 of the drawings, which is a block diagram of the system of a preferred embodiment of the present invention. In this system, the fuel is stored under pressure in a fuel storage tank 10, the pressure varying with the type of fuel, for example natural gas being typically stored at around 3000 psi and propane at less than 312 psi, the amount of fuel in the tank 10 and the temperature of the fuel.

From the storage tank 10, a fuel line 12 leads to a fuel pressure regulator 14, where the pressure of the stored fuel is reduced to a pressure suitable for metering, and also to ensure that the fuel is in the gas phase for metering. From the regulator 14, the fuel passes through a metering device or valve 16, which supplies fuel to an air/fuel mixer 18, typically downstream of the engine air intake 17, where the fuel mixes with intake air and is drawn into the engine 19.

The metering valve 16 supplies fuel in accordance with the fuel demands of the engine 19, which are determined from various sensors 20 for detecting engine operating parameters, and various further sensors 22 which detect parameters of the fuel and operating parameters of the metering valve 16. The readings obtained by the sensors 20, 22 are fed into a system controlling computer 24, which is programmed to operate metering valve 16 in accordance with the engine fuel requirements, as determined by manipulation of the sensor readings.

The fuel storage tank 10 and the fuel lines 12 are conventional, and as mentioned above, they supply fuel to the pressure regulator 14, which will now be described with reference to Figures 2 and 3 of the drawings. Reference is first made to Figure 2, which is a block diagram indicating the main components of the regulator 14, and the path of fuel therethrough (indicated by arrows 15). The fuel line 12 is attached to the regulator by means of a conventional inlet fitting. The fuel is then passed through a filter 26 to remove any particulate matter from the fuel. Downstream of the filter 26 is a high pressure shut-off solenoid 28, which is used to shut off the fuel supply when the engine is turned off.

The pressure of the fuel is a function of the amount of fuel in the fuel storage tank 10, and also of the fuel temperature. Thus, by measuring the fuel temperature and pressure, the amount of fuel in the tank can be determined. A high pressure sensor 30 is provided in the regulator for this purpose, downstream of the shut-off solenoid 28. A signal from the sensor 30 is supplied to the system computer 24, which is programmed to combine the pressure reading with the reading from a temperature sensor (not shown) to provide a fuel level indication.

Downstream of the solenoid 28, the high pressure fuel passes through an adjustable pressure regulator valve 32 which is adjusted to lower the pressure of the fuel to a desired level, for example, natural gas stored at 3000 psi may be reduced to a pressure of 100 psi.

The sudden expansion of the fuel results in a corresponding drop in fuel temperature. Particularly when using gaseous fuel, it is desirable to maintain the fuel temperature fairly close to ambient to maintain its state and maximize its energy density: with propane, a sufficiently low temperature may result in the propane returning to the liquid phase; and with natural gas less dramatic drops in temperature may result in the formation of "hydrates", a spongy, ice-like material formed by water present in the fuel freezing and forming a lattice with fuel molecules which will obstruct and block the flow of fuel. This cooling is overcome by heating the block, in this example by passing engine cooling fluid through a passage 34 in the regulator block.

In the event of a failure of the regulator valve 32, possibly combined with the failure of the solenoid 28, the high pressure of, for example, stored natural gas could result in the explosive destruction of the regulator. In order to minimize this possibility, a pressure relief valve 36 is provided downstream of the regulator 32, to allow for the release of pressure above a predetermined limit, before damage to the regulator 14 and metering valve 16 occurs.

Reference is now made in particular to Figures 3a-3e of the drawings which illustrate the arrangement of the various components of the pressure regulator 14, mounted on a regulator block or body 38. As the regulator assembly must be accommodated in the restricted space of a vehicle engine compartment, the assembly is compact and is arranged such that the various connections between the assembly and other
5 engine components can be made conveniently and in a space-efficient manner.

For ease of description and understanding, the regulator assembly will be described with reference to the particular orientation of the regulator seen in Figure 3a, which illustrates the regulator body 38, a regulator valve assembly 32 mounted on an upper portion of the body, a high pressure solenoid 28 mounted on the side of the body, and a high pressure sensor 30 and relief valve assembly 36 mounted on
10 a lower portion of the body.

An inlet fitting 42 (Figure 3d) is provided for connection to the fuel line 12 leading from the fuel storage tank 10. The fitting 42 is attached to the main regulator body 38 at the mouth of an inlet passage 44 and is located in a stepped cylindrical passage 45 which accommodates a cylindrical section sintered metal filter 26, preferably fabricated of steel or brass. The filter 26 is relatively long (typically 2 cm), and has a
15 correspondingly large surface area, such that the pressure drop over the filter 26 is minimal. Further, in the unlikely event of the filter 26 becoming blocked, the filter 26 is strong enough to withstand the pressure exerted by the fuel and will not collapse and damage the interior of the regulator. The filter 26 is held in place by a retaining spring 46 one end of which abuts a surface of the inlet fitting 42, and seats on an annular gasket 48 located around the mouth of the passage 44.

20 Directly downstream of the inlet passage 44 is the high-pressure solenoid 28 (Figure 3a), which, when deenergized, isolates the regulator 14 from the fuel storage tank 10. The passage 44 intersects with a first inlet chamber 51 for communication with an inlet orifice 53 leading to a second main inlet chamber. The solenoid coil 50 will normally be activated on turning on the ignition of the vehicle to allow passage of fuel between the chamber 51 and the orifice 53, and due to the relatively high pressure of the fuel supply, a
25 solenoid having magnetically latched pilot and primary pistons 52, 54 is provided, the operation of which will be described below.

The solenoid coil 50 is contained within a suitable casing 56, mounted on the body by means of a solenoid tube 58. The coil 50 is of course hollow and accommodates a smooth-walled, cylindrical portion 60 of the tube 58. A threaded, first end 62 of the tube 58 extends from a centrally located aperture 64 in the
30 casing 56, and receives a complementary nut 66 which secures the casing 56 and coil 50 on the tube 58. The other end 68 of the tube is also threaded, but is of greater cross-section than the first end 62 and is adapted to engage a threaded bore 70 in the regulator body 38.

The tube 58 is solid over approximately half of the length from the first end 62. The remainder of the tube 58 is hollow and accommodates the pistons 52, 54. The primary piston 54 extends beyond the other
35 end of the tube 58. When the solenoid is deactivated the inlet orifice 53 is closed, the primary piston 54 bearing against the surface of an annular raised portion 74 which surrounds the orifice 53. The proximal end of the piston is provided with an annular recess 78 to accommodate a resilient annular pad 80 to form a seal with the raised portion 74. A central bore 81 extends through the piston 54 and the pad 80 to the distal end of the primary piston 54, adjacent the pilot piston 52. The distal end of the primary piston 54 is
40 provided with a raised nipple 84 with a relatively small diameter throughbore 90 (typically 0.016" dia.).

The piston 54 is substantially cylindrical and is a fairly close fit in the tube. To provide for fluid communication between the first inlet chamber 51 and the gap 88 between the ends of the pistons, the proximal end of the primary piston is tapered, and four longitudinal slots 92 are provided in the outer surface of the piston, the purpose of the slots being described hereinbelow.

45 In the closed configuration, the end of the pilot piston 52 bears against the nipple 84 of the primary piston 54 to close the throughbore 90. The end of the piston 52 is provided with a cylindrical recess 94 to accommodate a resilient cylindrical pad 96 which bears against the nipple 84. The distal end of the pilot piston features a frusto-conical portion 102, the end of this portion including an annular bearing surface 104 and a cylindrical stub 106 for mounting a coil spring 108, the opposite end of which bears against the end
50 wall 110 of the tube. The spring 108 tends to push the pistons 52, 54 to close the inlet orifice 53. The spring 108 is located in a cylindrical recess 112 in the tube, and the end of tube 58 is provided with a 60° conical taper at 114, corresponding to the taper on the end of the pilot piston 52, the tapering ends of the piston and tube 58 allowing for a longer pull of the piston.

When the coil 50 is energized, the pilot piston 52 is pulled towards the end wall 110, against the spring
55 108. Initially, the primary piston 54 remains in place, as the pressure force acting on the distal end of the piston 54 is greater than the pressure force exerted by the gas in the main inlet chamber, exerted over the area of the orifice 53, and the pull on the piston 54 from the energized solenoid 50. When the pilot piston 52 is retracted, the end of the throughbore 90 is uncovered, and the high pressure gas from the inlet

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passes from the inlet chamber 51, through the slots 92 to the distal end of the piston 54, into the bore 81 and the orifice 53. After a short time, the pressure in the orifice 53 rises to a level whereby the net pressure forces on the piston 54 are negligible, and the pull on the piston from the energized solenoid is sufficient to retract the piston 54 allowing gas to flow past the proximal end of the piston directly from the inlet and

5   through the orifice 53.

The orifice 53 extends into a main inlet chamber, which is in the form of a chamber 116 formed in a central bore in the body. The pressure sensor 30 forms one end wall of the chamber 116, and has a threaded coupling portion 120 for engaging a complementary threaded portion 122 of the bore. The opposite end of the bore is provided with a metering orifice 127 which accommodates the metering pintle

10   126 of the adjustable regulating valve 32. The metering orifice leads into an outlet chamber 160.

The valve assembly 32 is mounted on an upper portion of the regulator body 38 and is contained within a spring tower or casing 128 in the form of a zinc casting with a threaded lower portion 130 for engaging a complementary threaded portion 132 on the regulator body 38, and having a breather hole 133 above the lower threaded portion 130. The upper end of the casing 128 accommodates a compression spring 134, the

15   upper end of the spring bearing against a spring end plate 136, the position of the plate being controlled by adjusting a recessed adjusting screw 138 located in a threaded bore 140 in the upper end of the casing 128.

The metering pintle 126 includes an enlarged cylindrical head with a conical base, a resilient pintle seal 142 being positioned between the head and the metering orifice 127. An elongate portion 143 of the pintle

20   126 extends through the orifice 127 and engages a pintle retainer 144 which retains the metering pintle in the orifice 127.

The pintle retainer 144 abuts a diaphragm end cap 155 which is mounted to a spring plate 158. The lower end of the compression spring 134 bears on the spring plate 158, through a cup-shaped spring damper 156, and through the spring plate 158 and a diaphragm backing washer 152 on a diaphragm 150

25   which is mounted by means of a downturned edge in an annular groove 151 on the upper end of the body 38. The diaphragm is retained in position by the clamping action of the casing on the body 38. On the other side of the diaphragm 150 is a damper spring 146 which lies within the return spring washer 148 and extends between the lower face of the diaphragm 150 and the regulator body 38.

Positioned between the sides of the pintle retainer 144 and the diaphragm end cap 155 is a bushing

30   portion of a diaphragm stop 154, also having a flange portion which projects outwardly from the bushing portion, lies within the return spring washer 148, and is situated vertically between the diaphragm 152 and the body 38, thus limiting the downward movement of the diaphragm 150. The flange portion lies above a raised cruciform configuration 154a on the body 38 above the metering orifice 127.

To adjust the regulator, the position of the spring end plate 136 is varied, which changes the downward

35   spring force on the diaphragm 150. The spring force is counter-balanced by the pressure of the regulated fuel in the chamber 160 acting on the other side of the diaphragm 150. When the pressure in the chamber 160 drops, the spring force will thus lift the pintle from the sealing position at the orifice 127 and allow fuel to flow past the pintle 126, the pressure of the fuel being reduced as the fuel is throttled on passing the pintle.

40   The lower pressure gas flows into the annular chamber 160, which is formed in a channel in the upper end of the regulator body, the channel being deepened over an arc-shaped portion 162, one end of which communicates with an outlet fitting 166 (see Figure 3b). The fitting 166 is located in a bore which intersects one end of the arc-shaped portion 162.

The relief valve 36 (Figure 3c) is located in a cylindrical bore 174 in the base of the body, which

45   intersects a horizontal relief bore 177, the bore 174 extending into a smaller diameter bore extension 176, which intersects the other end of the arc-shaped portion 162. The relief valve normally seals the end of the bore extension 176, and when opened by a higher than normal pressure in the chamber 160 allows gas to flow from the regulator through one of two alternate outlets. In this example an outlet 179 at one end of the relief bore 177 is plugged, while an upright outlet fitting 181 is provided in a bore 183 which intersects the

50   other end of the relief bore 177.

The relief valve 36 is shown in more detail in Figure 3e, being illustrated in the open configuration, and comprises a valve housing 180, a relief valve piston 182 normally held to close the valve opening 188 at the base of the bore 176, and a compression spring 184 which acts between the piston 182 and the housing 180. The end 186 of the piston 182 that closes the relief valve opening 188 includes a relief valve seat 190,

55   held in place by a plated washer 192 and plated machine screw 194.

The end of the spring 184 not acting on the piston is mounted on a spring end positioner 198, the location of which may be adjusted by an adjusting screw 200, accessible from the exterior of the regulator.

The end of the housing 180 includes a vent opening 202 provided with a vent filter 204. O-ring seals

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206, 208 are provided between the housing 180 and body 38 and the relief valve piston and housing.

With the valve in the open configuration, as illustrated, fuel may flow from the chamber 160, into the bore 176, past the end of the piston 182 and into the relief bore 177. From the relief bore the fuel flows through the outlet fitting 181 (Figure 3c), which may be provided with a hose to carry the fuel away from the engine.

In the event of a regulator valve failure, the flow capabilities of the relief valve and the associated outlets do not permit the build-up of dangerously high pressures in the regulator. This should prevent the destruction of the regulator and subsequent damage to the vehicle.

As was mentioned above, the expansion of the fuel in the regulator results in cooling of the fuel. It is desirable to minimize this net cooling, to prevent the temperature of the fuel falling below the critical temperature and returning to the liquid phase (propane only). Also hydrates may form in the cooled fuel, resulting in restriction and blocking of the regulator flow path. While these hydrate problems are primarily associated with fuels such as natural gas, rather than propane, it is also generally preferable to maintain the regulator at a sufficient temperature to prevent the build-up of ice on the exterior of the body.

The heating of the regulator is achieved by use of the engine coolant, typically water and "anti-freeze", which is passed through the body 38. The heating fluid inlet 210 is located on a lower portion of the body (see Figure 3b). An alternate inlet is provided at 211 on the side of the body, the inlet not in use being plugged (in this example, inlet 211 is plugged). The heating fluid passage 34 extends in a U-shaped path through the body to an outlet 212 adjacent the inlet 210. The passage 34 is adjacent the fuel inlet 44, which is located in the "deepest" portion of the regulator, and thus the routing of the passage through this portion provides a long heat path and thus is more effective in heating the regulator.

From Figure 3b is will also be noted that one side of the body is provided with a planar mounting surface 214 provided with threaded bores 216 to receive bolts extending from some suitable mounting structure. It will also be noted that the mounting side of the regulator is free of inlets and outlets which might make mounting more difficult.

From the regulator 32, the fuel, now at a suitable pressure for metering, passes through conduits to the metering valve 16, illustrated in block diagram form in Figure 4 of the drawings, and further in Figures 5-7 of the drawings, reference being made first to Figure 4. The regulated fuel passes from the regulator through an inlet 220 provided with a filter 221 into an inlet manifold 222. The manifold communicates with, in this example, eight bi-stable fuel injectors and leads to an outlet 233 linked to the air/fuel mixer. Various sensors and control circuitry are illustrated in Figure 4 and will be described hereinbelow following a physical description of the metering valve and its various elements.

For each description, Figure 5a is designated a top plan view, and Figures 5b and 5c represent front and side elevations of the metering value. Further, the term longitudinal, when used herein with reference to the valve body, indicates a direction perpendicular to the section line 6-6 of Figure 5A, while the term transverse indicates a direction parallel to the section line.

As mentioned above with reference to Figure 4, the fuel passes through the inlet 220 provided with a filter into a main inlet manifold 222 and communicates with eight bi-stable fuel flow control valves on 224-231 with orifices of various sizes. Six "high-flow" injectors 224-229 are mounted in the same plane, and two "low-flow" or pulsing injectors 230, 231 are mounted parallel to one another perpendicular to the other injectors, between mounting posts 300, 302. A common outlet manifold 232 communicates with the outlets of the injectors and leads to a valve outlet 233. (Fig. 4).

The inlet manifolding is arranged such that all injector orifices operate at substantially the same stagnation pressure, regardless of which combination of orifices is flowing. Further, the outlet manifolding is arranged such that all orifices operate at a back pressure low enough to assure that each injector orifice remains sonic, regardless of which combination of orifices is flowing. In this description, the term sonic is used to indicate choked flow in the orifice, or that the pressure differential across the orifice is such that variations in downstream pressure do not affect the flow rate through the orifice. The manifolding will be described with reference primarily to Figures 7a-7d of the drawings, the description of the inlet manifolding being followed by a description of the injector configuration, as shown in Figure 6 of the drawings and, subsequently, by a description of the outlet manifolding.

Figures 7a-7b illustrate the metering valve block 17, and each one of the Figures illustrates a different aspect of the valve body manifolding. Reference is first made to Figure 7a, which illustrates the inlet manifolding.

The inlet 220 is located in an end face of the valve body. An inlet fitting 304 (Figur 5a) is provided and comprises a hose connector portion 306, for fitting within the connecting hose (not shown) leading downstream from the regulator. The lower portion of the fitting 304 engages within a collar 308 that extends from the valve body and accommodates a filter (not shown). Extending from the collar 308 and into the

valve body is a cylindrical longitudinal bore 310, which intersects two parallel longitudinal bores 312, 314 extending from the other end of the valve body. These bores 312, 314 intersect the upright bores provided for accommodating the six high-flow injectors 224-229. A transverse bore 316 intersects the inlet bore 310 to supply fuel to the low-flow injectors 230, 231, and is in communication with an upright inlet bore in

5 communication with injector inlets at the top end of the injectors 230, 231, in the mounting post 300.

For the low-flow injectors it is also possible to extend the inlet bore to provide traps for the collection of impurities in the fuel, this being particularly useful for use in propane metering, propane often containing an oily/powdery residue that might otherwise block the orifices.

As is evident from the Figures, and the inlet manifolding configuration, the gas feed location differs

10 between the low-flow and high-flow injectors, i.e., the low-flow injectors utilize top feed whereas the high-flow injectors utilize bottom feed. Figure 6 is an enlarged sectional view through a portion of the metering valve and illustrates details of two high-flow injectors (mountings for the low-flow injectors not shown). The injector 224 illustrated in the right hand side of Figure 6 is shown closed, and the injector 225 shown on the left hand side of the Figure is shown in the open position, providing a flow path 234 for fluid from the inlet

15 manifold 222 or bore 314 through the injector orifice 236, to the outlet manifold 233 (Fig. 4). The orifice 236 is formed in a non-magnetic insert 238 which is fitted into a larger opening 240 in the body of the metering valve or alternatively as a permanent part of a unit injector. However, providing a separate insert allows each injector to be constructed from standard parts, differing only in the insert, or more particularly in the orifice size in the insert.

20 The insert 238 includes a substantially cylindrical upper portion 242, with a flange 243 formed at the base thereof, sized for a snug fit within the 240 and which engages an inward step of the opening. The orifice 236 is located in the centre of the upper portion 242, surrounded by a raised lip 244 which extends beyond the planar upper surface of the portion 242.

Directly below the flange 243 is a portion 246 of slightly smaller diameter than the opening 240, and

25 below this portion is a portion 248 of diameter substantially corresponding to the opening 240, which creates an annular space 250 between the insert and the wall of the opening. A resilient O-ring 252 is located in the space 250.

The orifice extends through the insert and is preferably of the converging diverging type, having a short cylindrical portion 258 and a frusto-conical portion 260 which opens into the outlet manifold. With an orifice

30 of this form, the pressure differential necessary to provide sonic flow through the orifice may be as low as 15%, whereas for a sharp-edged orifice the pressure differential may have to be as high as 53%.

To provide an immediately available reservoir of fuel when the injector opens, the upper portion 242 of the insert is located in a chamber 262 formed in the valve body, which provides, surrounding the orifice opening, a space which one of the bores 312, 314 intersects. The upper portion of each chamber

35 accommodates a lower portion of a magnetic injector plunger 264, which is movable to open and close the orifice. The lower end face 266 of the plunger is provided with a resilient washer seal 268 to form a seal with the raised lip 244 of the insert when the injector is closed. Alternatively, metal to metal sealing may be used. A non-magnetic injector core tube 284 slidably receives the plunger 264, the tube including a seating portion 286 which sits in an enlarged portion 288 of the chamber 262, the seating portion 286 itself forming

40 an upper wall of the fuel receiving part of the chamber 262. The seating portion 286 is substantially annular and includes a circumferential groove 290 having a sloping base, to provide a space between the seating portion 286 and the valve body for accommodating a resilient O-ring 292. A compression spring 285 is mounted on the plunger 264 and seats against the core tubes creating a force which causes the plunger to seal against the orifice.

45 The upper portion of the core tube fits within a magnetic coil case 294 adapted to accommodate the injector coil. The case is mounted on an upper surface of the core tube seating portion and the valve body.

As mentioned above, the low-flow injectors in this example of a metering valve utilize top flow and are, in fact, conventional gasoline injectors, such as a Lucas type FJ12.

Below the high-flow injectors are longitudinal bores 320, 321 for receiving the gas after it has passed

50 through the injectors. Three of the injectors communicate with a main outlet bore 320 (see Figure 7b) while the other three communicate with a smaller diameter bore 321 that is linked to the main outlet bore 320 by a transverse bore 322 (Fig. 7b). The transverse bore 322 also intersects the outlets of the low-flow injectors in the post 302. The main outlet bore 320 extends to the end of the valve body and accommodates an outlet fitting 334, which includes a hose connector 326 (see Figure 5c).

55 For ease of construction, the valve body is formed by drilling a solid block. The various bores are formed by drilling the block, the open ends of the bores being sealed by plugs.

The particular valve illustrated is intended for use in metering both natural gas and propane, though for a typical propane application it is likely that the valve would be provided with a greater number of injectors

and the injectors would be provided with orifice inserts having larger area orifices (the propane is at lower pressure and, therefore, has a greater volume). In both natural gas and propane applications it is desired to keep the fuel from cooling to the degree that hydrates will form in the fuel or that the fuel will return to the liquid state, as discussed above. To minimize this possibility, the valve body is provided with a passage 450
5   (Figure 7c) for conveying a heating fluid, typically the engine cooling fluid, in a manner similar to the regulator. The passage extends around the six high-flow injector bores. The passage begins at an inlet 452 (Figure 5c) provided with a suitable inlet fitting which is received by a short, cylindrical longitudinal bore which intersects an upright bore 454 which leads to a solenoid chamber 456. A solenoid 458 (Figure 5c) is mounted on the end of the valve block and is operated to control the flow of fluid through the passageway,
10 which is formed by three intersecting bores 460, 462, 464.

The lower portion of the block is provided with a recess 466 (Fig. 7d) which accommodates various sensors and the power transistor circuitry necessary to operate the injectors. Three pressure sensors are provided in the valve body: an outlet pressure sensor 340 (Figures 5d and 7b) which measures the pressure of the fuel downstream of the injectors by means of a plugged transverse bore 341 which intersects the
15 main outlet bore 320 and which communicates with the sensor 340, mounted through an upright bore 342 which extends from the recess; an inlet or regulated pressure sensor 334 (Figures 5d, 7a and 7b) located in an upright bore 338 which communicates with a transverse bore 336, which intersects an inlet bore 312 (Figure 7d); and an intake manifold absolute pressure (MAP) sensor 343 which measures the pressure in the engine intake manifold via a vacuum hose. By recording the pressure sensed by the outlet pressure
20 sensor before starting the engine it is also possible to obtain a reading for barometric pressure. A regulated fuel temperature sensor may also be provided (Figure 4).

As is seen most clearly in Figure 7d, the inlet pressure sensor transverse bore 336 just "nicks" the inlet bore 312 and the communicating opening between bores is located in an upper wall of the bore 312. This is intended to minimize the ingress of any dirt or impurities in the fuel into the pressure sensor manifolding.
25 The outlet pressure sensor manifolding is similarly arranged.

A temperature sensor may also be provided for measuring the temperature of the fuel in the outlet bore from the low-flow injectors.

The sensors are all connected to a metering valve electronic control board 344 (Figure 6) carrying the power transistor circuitry which operates the injectors. During operation of the injectors, the circuitry
30 generates heat which is dissipated through the valve body. Figure 4 includes a representation of the various sensors and the associated circuitry. An external connector 346 (Figure 5d) is provided at one end of the board 344 and extends through an opening 348 in the recess wall 350.

The open end of the recess may be covered with a rectangular cover 352 which is attached to the valve body using fastening screws.
35 As mentioned above, the system control computer selectively operates the injectors to provide a desired fuel flow to the engine. The control system includes sensors to detect various engine parameters and the fuel condition, and thus determine the fuelling needs of the engine. Various other operating parameters of the system and the engine ancillaries are also determined, and are utilized to provide accurate control of the metering valve and thus accurate fuelling of the engine. A description of the control
40 system and the various associated sensors, will follow hereinafter.

The variation in fuel flow is provided by opening selected ones of the high-flow injectors to provide a base flow component, and preferably also by opening at least some of the low-flow injectors for predetermined timed intervals, or by "pulsing" the low-flow injectors.

The orifice sizes of the injectors are selected to provide a suitable series of flow areas which can be
45 manipulated to provide accurate fuelling over a wide dynamic range, typically 1:40 or 1:35. The orifice sizing, or more precisely the different mass flows of fuel through each injector orifice, requires careful selection in order to minimize the number of injectors required, and reduce the number of injector closings occurring.

Sonic mass flow through an orifice is:
50

$$Q(actual) = C.A.P.\sqrt{\frac{g.k}{R.T.}\left(\frac{2}{(k+1)}\right)} (k+1)/(k-1) \qquad (1)$$

55 Where C = orifice discharge coefficient
A = orifice area
P = absolute supply stagnation pressure

10

g = a dimensional constant

k = specific heat ratio of the fluid (temp. dependant)

T = stagnation temperature of gas just before the orifice

R = specific gas constant

C, A, g are constant for each orifice, the combined effects of A and C being determined by testing each individual orifice during assembly of the metering valve, while P and T are determined by sensors to provide the actual flowrate for each orifice and k and R may be assumed for the known gas or be more accurately estimated from sensor data. For simplicity, the following description of the orifice flowrate sequences is in respect of conditions of constant temperature and pressure.

Each metering orifice M_o, M_1, M_2, M_3 and M_n provides a respective gas flow Q_o Q_1, Q_2, Q_3 and Q_n.

In one ideal sequence, the orifice sizes are selected such that the mass flow follows the sequence:

$Q_o = 2^{\bullet} Q_o = 1 \times Q_o$

$Q_1 = 2^{\bullet} Q_o = 1 \times Q_o$

$Q_2 = 2^1 Q_o = 2 \times Q_o$

$Q_3 = 2^2 Q_o = 4 \times Q_o$

.
.
.

$Q_{n-1} = 2^{n-2} Q_o$

$Q_n = 2^{n-1} Q_o$

Note: in a non-ideal valve the mass flows for the first two units (Q_o and Q_1) would each need to have a flowrate somewhat greater than $1 \times Q_o$ (ideal).

In this sequence it will be noted that the flowrates, apart from the first two, vary according to natural binary.

In a further ideal sequence, the orifice sizes are selected such that the mass flow follows the sequence:

$Q_o = 2^0 Q_o = 1 \times Q_o$

$Q_1 = 2^0 Q_o = 1 \times Q_o$

$Q_2 = 2^1 Q_o = 2 \times Q_o$ $Q3 = 2^2 Q_o = 4 \times Q_o$.

.
.
.

$Q_{n-1} = 2^{n-2} Q_o$

$Q_n = 2^{n-2} Q_o$

Note: in a non-ideal valve the mass flows for the first two units (Q_o and Q_1) would each need to have a flowrate somewhat greater than $1 \times Q_o$ (ideal).

It will be noted that the flowrates, apart from the first two, and the last flowrate, which is equal to second last flowrate, vary according to natural binary.

In the preferred ideal sequence, the orifice sizes are selected such that the mass flow follows the sequence.

$Q_o = 2^0 Q_o = 1 \times Q_o$

$Q_1 = 2^0 Q_o - 1 \times Q_o$

$Q_2 = 2^1 Q_o = 2 \times Q_o$

$Q_3 = 2^2 Q_o = 4 \times Q_o$

.
.
.

$Q_{n-3} = 2^{n-2} Q_o$

$Q_{n-2} = 2^{n-3} Q_o$

$Q_{n-1} = (Q_{n-3}) + (Q_{n-2}) = 2^{n-4} Q_o + 2^{n-3} Q_o = (2^{n-4} + 2^{n-3}) Q_o$

$Q_n = (Q_{n-3}) + (Q_{n-2}) = 2^{n-4} Q_o + 2^{n-3} Q_o = (2^{n-4} + 2^{n-3}) Q_o$

Note: in a non-ideal valve the mass flows for the first two units (Q_o and Q_1) would each need to have a flowrate somewhat greater than $1 \times Q_o$ (ideal).

It will be noted that the flowrates, apart from the first two, and the last two flowrates which are equal and also the sum of the third and fourth last flowrates, vary according to natural binary.

As the sequences are similar, apart from the last two orifice flow rates, each will be referred to by reference to the last two "units" of flow, that is, last two units use natural binary (LNB), last two units have equal output (L2E), and last two units equal the sum of the previous two units (L2S).

There follows tables of ideal and practical configuration with actual flowrates for orifices following such sequences, to provide a maximum flow of 3000 standard cubic feet per hour (SCFH).

11

Injector Number	LNB	L2E	L2S
1	0-47	0-63	0-75
2	0-47	0-63	0-75
3	94	125	150
4	188	250	300
5	375	500	600
6	750	1000	900
7	1500	1000	900
Total	3001	3001	3000

In preferred systems, the total flow from the first two injectors will exceed the flow from the third injector, as mentioned in the notes above. This arrangement is preferred for two reasons: only a fraction of an injector's steady state flow capability can be used when the injector is "pulsing" to provide a continuously variable output flowrate, such that some "reserve" capacity is required; and if reserve of "excess" flow exists, it can be used to compensate for both transient and steady state flow errors from all of the injectors.

The use of only a fraction of an injector's steady state flowrate requires the pulsing injector to be shut off once each metering cycle. A typical (empirically supported) pulsed injector flow model can be expressed as:

$$Q[T] \quad = \quad Q_s \left[\frac{T_{on} - T_{open} + T_{close}}{T_{on} + T_{off}} \right]$$

WHERE $Q[T]$ = Pulsing injector flow rate
Q_s = Steady state injector flow rate
T_{on} = Injector on time control signal duration
T_{open} = Time for injector to open
T_{close} = Time for injector to close
$T_{on} + T_{off}$ = Time between spark plug firings

For example, a typical injector may require 1200 μs to open and 900 μs to close. If the metering cycle were on a 6 cylinder engine running at 5200 rpm, then one cycle would last 3846 μs (i.e. the time between spark plug firings).

For such an injector the nominal minimum pulsed on time would be $T_{on} = T_{open}$, and the nominal maximum pulsed on time would be $T_{on} = T_{on} + T_{off} - T_{close}$. Under these conditions, a reasonable injector flow model predicts the minimum useable injector pulsed flow rate to be 900/3846ths (or 23.4%) of its steady state flow rate. As well, the injector's maximum predictable pulsed flow rate would be (3846 - 1200)/3846ths (or 68.8%) of its steady flow rate.

In the following sequence, a series of injector TRUTH TABLES are provided which illustrate examples of achieving, by various valve designs, a range of fuel flows. In each case, a range of flowrates is given for the injectors which are pulsed (once per combustion event) for the length of time required to provide the required average flow rate. Examples are provided where the first two or three injectors are pulsed. In all cases, the sum of the steady state flow of the pulsing injectors is greater than the output of the next injector. Notably, the first injector is never allowed to output its full steady state output for the reason noted above where only 68.8% availability of the steady flow was available at 5200 rpm. However, all other pulsing injectors may be operated at 100% of their output, if required, by merely leaving them on all of the time.

The first TRUTH TABLE includes a column headed 'Overlap', which indicates the variation of flow at particular lines which may be obtained using the same injector or value configuration by varying the pulse width or the open time of the first injector.

12

Box text: L254.5 Qmax=2746 Clsg= 23

LINE NO	TOT FLOW min	max	#1 88 (0)	#2 88	#3 110	#4 220	#5 440	#6 900	#7 900	OVER LAP	7	6	5
1	0	61	0 - 61										
2	62	116	31 - 58	31 -58									
3	117	168	29 - 80	88 -88							6%	9%	18%
4	169	171	59 - 61		110					34.9%	6%	9%	18%
5	172	226	31 - 58	31 -58	110						8%	12%	24%
6	227	278	29 - 80	88 -88	110						10%	15%	29%
7	279	281	59 - 61			220				21.1%	10%	15%	30%
8	282	336	31 - 58	31 -58		220					12%	18%	36%
9	337	388	29 - 80	88 -88		220					14%	21%	41%
10	389	391	59 - 61		110	220				15.2%	14%	21%	41%
11	392	446	31 - 58	31 -58	110	220					16%	24%	47%
12	447	498	29 - 80	88 -88	110	220					18%	27%	53%
13	499	501	59 - 61				440			11.8%	18%	27%	53%
14	502	556	31 - 58	31 -58			440				20%	30%	59%
15	557	608	29 - 80	88 -88			440				22%	33%	64%
16	609	611	59 - 61		110		440			9.7%	22%	33%	65%
17	612	666	31 - 58	31 -58	110		440				24%	36%	71%
18	667	718	29 - 80	88 -88	110		440				26%	39%	76%
19	719	721	59 - 61			220	440			8.2%	26%	39%	76%
20	722	776	31 - 58	31 -58		220	440				28%	42%	82%
21	777	828	29 - 80	88 -88		220	440				30%	45%	86%
22	829	831	59 - 61		110	220	440			7.1%	30%	45%	
23	832	886	31 - 58	31 -58	110	220	440				32%	48%	
24	887	938	29 - 80	88 -88	110	220	440				34%	51%	
25	939	961	39 - 61					900		4.2%	35%	52%	
26	962	1016	31 - 58	31 -58				900			37%	55%	
27	1017	1068	29 - 80	88 -88				900			39%	58%	
28	1069	1071	59 - 61		110			900		5.5%	39%	58%	
29	1072	1126	31 - 58	31 -58	110			900			41%	61%	
30	1127	1178	29 - 80	88 -88	110			900			43%	64%	
31	1179	1181	59 - 61			220		900		5.0%	43%	64%	
32	1182	1236	31 - 58	31 -58		220		900			45%	67%	
33	1237	1288	29 - 80	88 -88		220		900			47%	70%	
34	1289	1291	59 - 61		110	220		900		4.6%	47%	70%	
35	1292	1346	31 - 58	31 -58	110	220		900			49%	73%	
36	1347	1398	29 - 80	88 -88	110	220		900			51%	76%	
37	1399	1401	59 - 61				440	900		4.2%	51%	76%	
38	1402	1456	31 - 58	31 -58			440	900			53%	79%	
39	1457	1508	29 - 80	88 -88			440	900			55%	82%	
40	1509	1511	59 - 61		110		440	900		3.9%	55%	82%	
41	1512	1566	31 - 58	31 -58	110		440	900			57%	85%	
42	1567	1618	29 - 80	88 -88	110		440	900			59%	88%	
43	1619	1621	59 - 61			220	440	900		3.6%	59%	88%	
44	1622	1676	31 - 58	31 -58		220	440	900			61%	91%	
45	1677	1728	29 - 80	88 -88		220	440	900			63%	94%	
46	1729	1731	59 - 61		110	220	440	900		3.4%	63%	94%	
47	1732	1786	31 - 58	31 -58	110	220	440	900			65%	97%	
48	1787	1838	29 - 80	88 -88	110	220	440	900			67%		
49	1839	1861	39 - 61					900	900	2.1%	68%		
50	1862	1916	31 - 58	31 -58				900	900		70%		
51	1917	1968	29 - 80	88 -88				900	900		72%		
52	1969	1971	59 - 61		110			900	900	3.0%	72%		
53	1972	2026	31 - 58	31 -58	110			900	900		74%		
54	2027	2078	29 - 80	88 -88	110			900	900		76%		
55	2079	2081	59 - 61			220		900	900	2.8%	76%		
56	2082	2136	31 - 58	31 -58		220		900	900		78%		
57	2137	2188	29 - 80	88 -88		220		900	900		80%		
58	2189	2191	59 - 61		110	220		900	900	2.7%	80%		
59	2192	2246	31 - 58	31 -58	110	220		900	900		82%		
60	2247	2298	29 - 80	88 -88	110	220		900	900		84%		
61	2299	2301	59 - 61				440	900	900	2.6%	84%		
62	2302	2356	31 - 58	31 -58			440	900	900		86%		
63	2357	2408	29 - 80	88 -88			440	900	900		88%		
64	2409	2411	59 - 61		110		440	900	900	2.4%	88%		
65	2412	2466	31 - 58	31 -58	110		440	900	900		90%		
66	2467	2518	29 - 80	88 -88	110		440	900	900		92%		
67	2519	2521	59 - 61			220	440	900	900	2.3%	92%		
68	2522	2576	31 - 58	31 -58		220	440	900	900		94%		
69	2577	2628	29 - 80	88 -88		220	440	900	900		96%		
70	2629	2631	59 - 61		110	220	440	900	900	2.2%	96%		
71	2632	2686	31 - 58	31 -58	110	220	440	900	900		98%		
72	2687	2746	29 - 88	88 -88	110	220	440	900	900				

INJECTOR TRUTH TABLE: L2S CONFIGURATION, 8 INJECTORS, 3 PULSING

LINE NO	TOTAL FLOW (SCFH) min	max	#1 59	#2 64	#3 64	#4 150	#5 300	#6 600	#7 900	#8 900
1	0 -	59	0 - 59							
2	60 -	91	28 - 59	32						
3	92 -	123	28 - 59	64						
4	124 -	155	28 - 59	64	32					
5	156 -	187	28 - 59	64	64					
6	188 -	209	38 - 59			150				
7	210 -	241	28 - 59	32		150				
8	242 -	273	28 - 59	64		150				
9	274 -	305	28 - 59	64	32	150				
10	306 -	337	28 - 59	64	64	150				
11	338 -	359	38 - 59				300			
12	360 -	391	28 - 59	32			300			
13	392 -	423	28 - 59	64			300			
14	424 -	455	28 - 59	64	32		300			
15	456 -	487	28 - 59	64	64		300			
16	488 -	509	38 - 59			150	300			
17	510 -	541	28 - 59	32		150	300			
18	542 -	573	28 - 59	64		150	300			
19	574 -	605	28 - 59	64	32	150	300			
20	606 -	637	28 - 59	64	64	150	300			
21	638 -	659	38 - 59					600		
22	660 -	691	28 - 59	32				600		
23	692 -	723	28 - 59	64				600		
24	724 -	755	28 - 59	64	32			600		
25	756 -	787	28 - 59	64	64			600		
26	788 -	809	38 - 59			150		600		
27	810 -	841	28 - 59	32		150		600		
28	842 -	873	28 - 59	64		150		600		
29	874 -	905	28 - 59	64	32	150		600		
30	906 -	937	28 - 59	64	64	150		600		
31	938 -	959	38 - 59						900	
32	960 -	991	28 - 59	32					900	
33	992 -	1023	28 - 59	64					900	
34	1024 -	1055	28 - 59	64	32				900	
35	1056 -	1087	28 - 59	64	64				900	
36	1088 -	1109	38 - 59			150			900	
37	1110 -	1141	28 - 59	32		150			900	
38	1142 -	1173	28 - 59	64		150			900	
39	1174 -	1205	28 - 59	64	32	150			900	
40	1206 -	1237	28 - 59	64	64	150			900	
41	1238 -	1259	38 - 59				300		900	
42	1260 -	1291	28 - 59	32			300		900	
43	1292 -	1323	28 - 59	64			300		900	
44	1324 -	1355	28 - 59	64	32		300		900	
45	1356 -	1387	28 - 59	64	64		300		900	
46	1388 -	1409	38 - 59			150	300		900	
47	1410 -	1441	28 - 59	32		150	300		900	
48	1442 -	1473	28 - 59	64		150	300		900	
49	1474 -	1505	28 - 59	64	32	150	300		900	
50	1506 -	1537	28 - 59	64	64	150	300		900	
51	1538 -	1559	38 - 59					600	900	
52	1560 -	1591	28 - 59	32				600	900	
53	1592 -	1623	28 - 59	64				600	900	
54	1624 -	1655	28 - 59	64	32			600	900	
55	1656 -	1687	28 - 59	64	64			600	900	
56	1688 -	1709	38 - 59			150		600	900	
57	1710 -	1741	28 - 59	32		150		600	900	
58	1742 -	1773	28 - 59	64		150		600	900	
59	1774 -	1805	28 - 59	64	32	150		600	900	
60	1806 -	1837	28 - 59	64	64	150		600	900	
61	1838 -	1859	38 - 59						900	900
62	1860 -	1891	28 - 59	32					900	900
63	1892 -	1923	28 - 59	64					900	900
64	1924 -	1955	28 - 59	64	32				900	900
65	1956 -	1987	28 - 59	64	64				900	900
66	1988 -	2009	38 - 59			150			900	900
67	2010 -	2041	28 - 59	32		150			900	900
68	2042 -	2073	28 - 59	64		150			900	900
69	2074 -	2105	28 - 59	64	32	150			900	900
70	2106 -	2137	28 - 59	64	64	150			900	900

INJECTOR TRUTH TABLE: [L2S] CONFIGURATION, 8 INJECTORS, 3 PULSING

LINE NO	TOTAL FLOW (SCFH) min	max	#1 59	#2 64	#3 64	#4 150	#5 300	#6 600	#7 900	#8 900
71	2138	2159	38 - 59				300		900	900
72	2160	2191	28 - 59	32			300		900	900
73	2192	2223	28 - 59	64			300		900	900
74	2224	2255	28 - 59	64	32		300		900	900
75	2256	2287	28 - 59	64	64		300		900	900
76	2288	2309	38 - 59			150	300		900 ·	900
77	2310	2341	28 - 59	32		150	300		900	900
78	2342	2373	28 - 59	64		150	300		900	900
79	2374	2405	28 - 59	64	32	150	300		900	900
80	2406	2437	28 - 59	64	64	150	300		900	900
81	2438	2459	38 - 59					600	900	900
82	2460	2491	28 - 59	32				600	900	900
83	2492	2523	28 - 59	64				600	900	900
84	2524	2555	28 - 59	64	32			600	900	900
85	2556	2587	28 - 59	64	64			600	900	900
86	2588	2609	38 - 59			150		600	900	900
87	2610	2641	28 - 59	32		150		600	900	900
88	2642	2673	28 - 59	64		150		600	900	900
89	2674	2705	28 - 59	64	32	150		600	900	900
90	2706	2737	28 - 59	64	64	150		600	900	900
91	2738	2759	38 - 59				300	600	900	900
92	2760	2791	28 - 59	32			300	600	900	900
93	2792	2823	28 - 59	64			300	600	900	900
94	2824	2855	28 - 59	64	32		300	600	900	900
95	2856	2887	28 - 59	64	64		300	600	900	900
96	2888	2909	38 - 59			150	300	600	900	900
97	2910	2941	28 - 59	32		150	300	600	900	900
98	2942	2973	28 - 59	64		150	300	600	900	900
99	2974	3005	28 - 59	64	32	150	300	600	900	900
100	3006	3037	28 - 59	64	64	150	300	600	900	900

INJECTOR TRUTH TABLE: L2S CONFIGURATION, 7 INJECTORS, 2 PULSING

LINE NO	TOTAL FLOW (SCFH) min	max	#1 90	#2 97	#3 150	#4 300	#5 600	#6 900	#7 900
1	0 -	90	0 - 90						
2	91 -	138	43 - 90	48					
3	139 -	187	42 - 90	97					
4	188 -	240	38 - 90		150				
5	241 -	288	43 - 90	48	150				
6	289 -	337	42 - 90	97	150				
7	338 -	390	38 - 90			300			
8	391 -	438	43 - 90	48		300			
9	439 -	487	42 - 90	97		300			
10	488 -	540	38 - 90		150	300			
11	541 -	588	43 - 90	48	150	300			
12	589 -	637	42 - 90	97	150	300			
13	638 -	690	38 - 90				600		
14	691 -	738	43 - 90	48			600		
15	739 -	787	42 - 90	97			600		
16	788 -	840	38 - 90		150		600		
17	841 -	888	43 - 90	48	150		600		
18	889 -	937	42 - 90	97	150		600		
19	938 -	990	38 - 90					900	
20	991 -	1038	43 - 90	48				900	
21	1039 -	1087	42 - 90	97				900	
22	1088 -	1140	38 - 90		150			900	
23	1141 -	1188	43 - 90	48	150			900	
24	1189 -	1237	42 - 90	97	150			900	
25	1238 -	1290	38 - 90			300		900	
26	1291 -	1338	43 - 90	48		300		900	
27	1339 -	1387	42 - 90	97		300		900	
28	1388 -	1440	38 - 90		150	300		900	
29	1441 -	1488	43 - 90	48	150	300		900	
30	1489 -	1537	42 - 90	97	150	300		900	
31	1538 -	1590	38 - 90				600	900	
32	1591 -	1638	43 - 90	48			600	900	
33	1639 -	1687	42 - 90	97			600	900	
34	1688 -	1740	38 - 90		150		600	900	
35	1741 -	1788	43 - 90	48	150		600	900	
36	1789 -	1837	42 - 90	97	150		600	900	
37	1838 -	1890	38 - 90					900	900
38	1891 -	1938	43 - 90	48				900	900
39	1939 -	1987	42 - 90	97				900	900
40	1988 -	2040	38 - 90		150			900	900
41	2041 -	2088	43 - 90	48	150			900	900
42	2089 -	2137	42 - 90	97	150			900	900
43	2138 -	2190	38 - 90			300		900	900
44	2191 -	2238	43 - 90	48		300		900	900
45	2239 -	2287	42 - 90	97		300		900	900
46	2288 -	2340	38 - 90		150	300		900	900
47	2341 -	2388	43 - 90	48	150	300		900	900
48	2389 -	2437	42 - 90	97	150	300		900	900
49	2438 -	2490	38 - 90				600	900	900
50	2491 -	2538	43 - 90	48			600	900	900
51	2539 -	2587	42 - 90	97			600	900	900
52	2588 -	2640	38 - 90		150		600	900	900
53	2641 -	2688	43 - 90	48	150		600	900	900
54	2689 -	2737	42 - 90	97	150		600	900	900
55	2738 -	2790	38 - 90			300	600	900	900
56	2791 -	2838	43 - 90	48		300	600	900	900
57	2839 -	2887	42 - 90	97		300	600	900	900
58	2888 -	2940	38 - 90		150	300	600	900	900
59	2941 -	2988	43 - 90	48	150	300	600	900	900
60	2989 -	3037	42 - 90	97	150	300	600	900	900

INJECTOR TRUTH TABLE: L2S CONFIGURATION, 8 INJECTORS, 2 PULSING

LINE NO	TOTAL FLOW (SCFH) min	max	#1 53	#2 58	#3 75	#4 150	#5 300	#6 600	#7 900	#8 900
1	0 -	53	0 - 53							
2	54 -	82	25 - 53	29						
3	83 -	111	25 - 53	58						
4	112 -	128	37 - 53		75					
5	129 -	157	25 - 53	29	75					
6	158 -	186	25 - 53	58	75					
7	187 -	203	37 - 53			150				
8	204 -	232	25 - 53	29		150				
9	233 -	261	25 - 53	58		150				
10	262 -	278	37 - 53		75	150				
11	279 -	307	25 - 53	29	75	150				
12	308 -	336	25 - 53	58	75	150				
13	337 -	353	37 - 53				300			
14	354 -	382	25 - 53	29			300			
15	383 -	411	25 - 53	58			300			
16	412 -	428	37 - 53		75		300			
17	429 -	457	25 - 53	29	75		300			
18	458 -	486	25 - 53	58	75		300			
19	487 -	503	37 - 53			150	300			
20	504 -	532	25 - 53	29		150	300			
21	533 -	561	25 - 53	58		150	300			
22	562 -	578	37 - 53		75	150	300			
23	579 -	607	25 - 53	29	75	150	300			
24	608 -	636	25 - 53	58	75	150	300			
25	637 -	653	37 - 53					600		
26	654 -	682	25 - 53	29				600		
27	683 -	711	25 - 53	58				600		
28	712 -	728	37 - 53		75			600		
29	729 -	757	25 - 53	29	75			600		
30	758 -	786	25 - 53	58	75			600		
31	787 -	803	37 - 53			150		600		
32	804 -	832	25 - 53	29		150		600		
33	833 -	861	25 - 53	58		150		600		
34	862 -	878	37 - 53		75	150		600		
35	879 -	907	25 - 53	29	75	150		600		
36	908 -	936	25 - 53	58	75	150		600		
37	937 -	953	37 - 53						900	
38	954 -	982	25 - 53	29					900	
39	983 -	1011	25 - 53	58					900	
40	1012 -	1028	37 - 53		75				900	
41	1029 -	1057	25 - 53	29	75				900	
42	1058 -	1086	25 - 53	58	75				900	
43	1087 -	1103	37 - 53			150			900	
44	1104 -	1132	25 - 53	29		150			900	
45	1133 -	1161	25 - 53	58		150			900	
46	1162 -	1178	37 - 53		75	150			900	
47	1179 -	1207	25 - 53	29	75	150			900	
48	1208 -	1236	25 - 53	58	75	150			900	
49	1237 -	1253	37 - 53				300		900	
50	1254 -	1282	25 - 53	29			300		900	
51	1283 -	1311	25 - 53	58			300		900	
52	1312 -	1328	37 - 53		75		300		900	
53	1329 -	1357	25 - 53	29	75		300		900	
54	1358 -	1386	25 - 53	58	75		300		900	
55	1387 -	1403	37 - 53			150	300		900	
56	1404 -	1432	25 - 53	29		150	300		900	
57	1433 -	1461	25 - 53	58		150	300		900	
58	1462 -	1478	37 - 53		75	150	300		900	
59	1479 -	1507	25 - 53	29	75	150	300		900	
60	1508 -	1536	25 - 53	58	75	150	300		900	
61	1537 -	1553	37 - 53					600	900	
62	1554 -	1582	25 - 53	29				600	900	
63	1583 -	1611	25 - 53	58				600	900	
64	1612 -	1628	37 - 53		75			600	900	
65	1629 -	1657	25 - 53	29	75			600	900	
66	1658 -	1686	25 - 53	58	75			600	900	
67	1687 -	1703	37 - 53			150		600	900	
68	1704 -	1732	25 - 53	29		150		600	900	
69	1733 -	1761	25 - 53	58		150		600	900	
70	1762 -	1778	37 - 53		75	150		600	900	

INJECTOR TRUTH TABLE: L2S CONFIGURATION, 8 INJECTORS, 2 PULSING

LINE NO	TOTAL FLOW (SCFH) min	max	OUTPUT FLOW USED FROM EACH INJECTOR #1 53	#2 58	#3 75	#4 150	#5 300	#6 600	#7 900	#8 900
71	1779	1807	25 - 53	29	75	150		600	900	
72	1808	1836	25 - 53	58	75	150		600	900	
73	1837	1853	37 - 53						900	900
74	1854	1882	25 - 53	29					900	900
75	1883	1911	25 - 53	58					900	900
76	1912	1928	37 - 53		75				900	900
77	1929	1957	25 - 53	29	75				900	900
78	1958	1986	25 - 53	58	75				900	900
79	1987	2003	37 - 53			150			900	900
80	2004	2032	25 - 53	29		150			900	900
81	2033	2061	25 - 53	58		150			900	900
82	2062	2078	37 - 53		75	150			900	900
83	2079	2107	25 - 53	29	75	150			900	900
84	2108	2136	25 - 53	58	75	150			900	900
85	2137	2153	37 - 53				300		900	900
86	2154	2182	25 - 53	29			300		900	900
87	2183	2211	25 - 53	58			300		900	900
88	2212	2228	37 - 53		75		300		900	900
89	2229	2257	25 - 53	29	75		300		900	900
90	2258	2286	25 - 53	58	75		300		900	900
91	2287	2303	37 - 53			150	300		900	900
92	2304	2332	25 - 53	29		150	300		900	900
93	2333	2361	25 - 53	58		150	300		900	900
94	2362	2378	37 - 53		75	150	300		900	900
95	2379	2407	25 - 53	29	75	150	300		900	900
96	2408	2436	25 - 53	58	75	150	300		900	900
97	2437	2453	37 - 53					600	900	900
98	2454	2482	25 - 53	29				600	900	900
99	2483	2511	25 - 53	58				600	900	900
100	2512	2528	37 - 53		75			600	900	900
101	2529	2557	25 - 53	29	75			600	900	900
102	2558	2586	25 - 53	58	75			600	900	900
103	2587	2603	37 - 53			150		600	900	900
104	2604	2632	25 - 53	29		150		600	900	900
105	2633	2661	25 - 53	58		150		600	900	900
106	2662	2678	37 - 53		75	150		600	900	900
107	2679	2707	25 - 53	29	75	150		600	900	900
108	2708	2736	25 - 53	58	75	150		600	900	900
109	2737	2753	37 - 53				300	600	900	900
110	2754	2782	25 - 53	29			300	600	900	900
111	2783	2811	25 - 53	58			300	600	900	900
112	2812	2828	37 - 53		75		300	600	900	900
113	2829	2857	25 - 53	29	75		300	600	900	900
114	2858	2886	25 - 53	58	75		300	600	900	900
115	2887	2903	37 - 53			150	300	600	900	900
116	2904	2932	25 - 53	29		150	300	600	900	900
117	2933	2961	25 - 53	58		150	300	600	900	900
118	2962	2978	37 - 53		75	150	300	600	900	900
119	2979	3007	25 - 53	29	75	150	300	600	900	900
120	3008	3036	25 - 53	58	75	150	300	600	900	900

INJECTOR TRUTH TABLE: L2E CONFIGURATION, 7 INJECTORS, 2 PULSING

LINE NO	TOTAL FLOW (SCFH) min	max	#1 80	#2 86	#3 125	#4 250	#5 500	#6 1000	#7 1000
1	0	80	0 - 80						
2	81	123	38 - 80	43					
3	124	166	38 - 80		86				
4	167	205	42 - 80			125			
5	206	248	38 - 80	43		125			
6	249	291	38 - 80		86	125			
7	292	330	42 - 80				250		
8	331	373	38 - 80	43			250		
9	374	416	38 - 80		86		250		
10	417	455	42 - 80			125	250		
11	456	498	38 - 80	43		125	250		
12	499	541	38 - 80		86	125	250		
13	542	580	42 - 80					500	
14	581	623	38 - 80	43				500	
15	624	666	38 - 80		86			500	
16	667	705	42 - 80			125		500	
17	706	748	38 - 80	43		125		500	
18	749	791	38 - 80		86	125		500	
19	792	830	42 - 80				250	500	
20	831	873	38 - 80	43			250	500	
21	874	916	38 - 80		86		250	500	
22	917	955	42 - 80			125	250	500	
23	956	998	38 - 80	43		125	250	500	
24	999	1041	38 - 80		86	125	250	500	
25	1042	1080	42 - 80						1000
26	1081	1123	38 - 80	43					1000
27	1124	1166	38 - 80		86				1000
28	1167	1205	42 - 80			125			1000
29	1206	1248	38 - 80	43		125			1000
30	1249	1291	38 - 80		86	125			1000
31	1292	1330	42 - 80				250		1000
32	1331	1373	38 - 80	43			250		1000
33	1374	1416	38 - 80		86		250		1000
34	1417	1455	42 - 80			125	250		1000
35	1456	1498	38 - 80	43		125	250		1000
36	1499	1541	38 - 80		86	125	250		1000
37	1542	1580	42 - 80					500	1000
38	1581	1623	38 - 80	43				500	1000
39	1624	1666	38 - 80		86			500	1000
40	1667	1705	42 - 80			125		500	1000
41	1706	1748	38 - 00	43		125		500	1000
42	1749	1791	38 - 80		86	125		500	1000
43	1792	1830	42 - 80				250	500	1000
44	1831	1873	38 - 80	43			250	500	1000
45	1874	1916	38 - 80		86		250	500	1000
46	1917	1955	42 - 80			125	250	500	1000
47	1956	1998	38 - 80	43		125	250	500	1000
48	1999	2041	38 - 80		86	125	250	500	1000
49	2042	2080	42 - 80					1000	1000
50	2081	2123	38 - 80	43				1000	1000
51	2124	2166	38 - 80		86			1000	1000
52	2167	2205	42 - 80			125		1000	1000
53	2206	2248	38 - 80	43		125		1000	1000
54	2249	2291	38 - 80		86	125		1000	1000
55	2292	2330	42 - 80				250	1000	1000
56	2331	2373	38 - 80	43			250	1000	1000
57	2374	2416	38 - 80		86		250	1000	1000
58	2417	2455	42 - 80			125	250	1000	1000
59	2456	2498	38 - 80	43		125	250	1000	1000
60	2499	2541	38 - 80		86	125	250	1000	1000
61	2542	2580	42 - 80					500	1000	1000
62	2581	2623	38 - 80	43				500	1000	1000
63	2624	2666	38 - 80		86			500	1000	1000
64	2667	2705	42 - 80			125		500	1000	1000
65	2706	2748	38 - 80	43		125		500	1000	1000
66	2749	2791	38 - 80		86	125		500	1000	1000
67	2792	2830	42 - 80				250	500	1000	1000
68	2831	2873	38 - 80	43			250	500	1000	1000
69	2874	2916	38 - 80		86		250	500	1000	1000
70	2917	2955	42 - 80			125	250	500	1000	1000
71	2956	2998	38 - 80	43		125	250	500	1000	1000
72	2999	3041	38 - 80		86	125	250	500	1000	1000

INJECTOR TRUTH TABLE: (LNB) CONFIGURATION, 7 INJECTORS, 2 PULSING

LINE NO	TOTAL FLOW (SCFH) min	max	#1 74	#2 80	#3 94	#4 188	#5 375	#6 750	#7 1500
1	0	74	0 - 74						
2	75	114	35 - 74	40					
3	115	168	21 - 74		94				
4	169	208	35 - 74	40	94				
5	209	262	21 - 74			188			
6	263	302	35 - 74	40		188			
7	303	356	21 - 74		94	188			
8	357	396	35 - 74	40	94	188			
9	397	449	22 - 74				375		
10	450	489	35 - 74	40			375		
11	490	543	21 - 74		94		375		
12	544	583	35 - 74	40	94		375		
13	584	637	21 - 74			188	375		
14	638	677	35 - 74	40		188	375		
15	678	731	21 - 74		94	188	375		
16	732	771	35 - 74	40	94	188	375		
17	772	824	22 - 74					750	
18	825	864	35 - 74	40				750	
19	865	918	21 - 74		94			750	
20	919	958	35 - 74	40	94			750	
21	959	1012	21 - 74			188		750	
22	1013	1052	35 - 74	40		188		750	
23	1053	1106	21 - 74		94	188		750	
24	1107	1146	35 - 74	40	94	188		750	
25	1147	1199	22 - 74				375	750	
26	1200	1239	35 - 74	40			375	750	
27	1240	1293	21 - 74		94		375	750	
28	1294	1333	35 - 74	40	94		375	750	
29	1334	1387	21 - 74			188	375	750	
30	1388	1427	35 - 74	40		188	375	750	
31	1428	1481	21 - 74		94	188	375	750	
32	1482	1521	35 - 74	40	94	188	375	750	
33	1522	1574	22 - 74						1500
34	1575	1614	35 - 74	40					1500
35	1615	1668	21 - 74		94				1500
36	1669	1708	35 - 74	40	94				1500
37	1709	1762	21 - 74			188			1500
38	1763	1802	35 - 74	40		188			1500
39	1803	1856	21 - 74		94	188			1500
40	1857	1896	35 - 74	40	94	188			1500
41	1897	1949	22 - 74				375		1500
42	1950	1989	35 - 74	40			375		1500
43	1990	2043	21 - 74		94		375		1500
44	2044	2083	35 - 74	40	94		375		1500
45	2084	2137	21 - 74			188	375		1500
46	2138	2177	35 - 74	40		188	375		1500
47	2178	2231	21 - 74		94	188	375		1500
48	2232	2271	35 - 74	40	94	188	375		1500
49	2272	2324	22 - 74					750	1500
50	2325	2364	35 - 74	40				750	1500
51	2365	2418	21 - 74		94			750	1500
52	2419	2458	35 - 74	40	94			750	1500
53	2459	2512	21 - 74			188		750	1500
54	2513	2552	35 - 74	40		188		750	1500
55	2553	2606	21 - 74		94	188		750	1500
56	2607	2646	35 - 74	40	94	188		750	1500
57	2647	2699	22 - 74				375	750	1500
58	2700	2739	35 - 74	40			375	750	1500
59	2740	2793	21 - 74		94		375	750	1500
60	2794	2833	35 - 74	40	94		375	750	1500
61	2834	2887	21 - 74			188	375	750	1500
62	2888	2927	35 - 74	40		188	375	750	1500
63	2928	2981	21 - 74		94	188	375	750	1500
64	2982	3021	35 - 74	40	94	188	375	750	1500

To accurately control the flow of fuel it is necessary to have the variables included in equation (1) above to calculate the mass flow of fuel through each orifice of the metering valve, and also to be able to predict the response times of individual injectors to "open" and "close" signals, and also the amount of fuel flowing through each orifice while the injector is changing states. These transient flowrates are affected by the operating voltage of the injector coil and the fuel pressure and temperature. The operating voltage and fuel pressure and temperature are readily obtained using appropriate sensors, while the injector coil temperature may be approximated by a control computer using fuel temperature, valve ambient temperature, injector on time, mass flowrate through the valve, and nominal heat rise and heat transfer characteristics of the injectors.

This information allows the fuel flow during the transient period to be predicted, such that the injectors are opened and closed at the correct times, and for the correct time periods.

The control system includes sensors 22a to detect the vehicle battery voltage (typically between 6 and 24 volts), as the response time of the injector will vary with the coil energizing voltage. The control system maintains the energizing current at, for example, 2 Amps., which is required to quickly open the injector and due to the low coil impedance assures that the injector will open even when the vehicle battery is operating at unusually low voltages. However, once the injector is open, the energizing current is reduced to 1/2 Amp. This feature, known as current foldback, in this example minimizes the generation of heat by the energized coil, prolongs coil life, and reduces the power consumption of the system and most importantly, reduces the time required for the magnetic field in the coil to collapse, which minimizes the injector closing period.

While injectors and orifices will be manufactured for specific orifice areas and consequently specific flowrates, there will still be small production variations in the orifice areas, and thus in the predicted flowrates, when compared to the "perfect" metering valve. To minimize fuelling errors and to avoid discontinuities in the fuel flow, each injector is tested, as mentioned above, such that the characteristics of each individual injector are known and can be introduced into the system control. The testing information may be provided in the form of a bar code, adhered to the injector or metering valve, which is bar code may be read when the system is being fitted to a vehicle.

Below are flow figures for an exemplary seven injector, L2S metering valve, for producing a maximum flow of 3000 SCFH.

Injector Number	All@ -2%	All@ Nominal	All@ +2%	Combinations	
				Min/Max	Random
1	73.5	75	76.5	76.5	73.5
2	73.5	75	76.5	73.5	73.5
3	147.0	150	153.0	150	146.0
4	294.0	300	306.0	294	306.0
5	588.9	600	612.0	612	588.0
6	882.0	900	918.0	882	918.0
7	882.0	900	918.0	918	918.0
Total	2940	3000	3060	3006	3023

	Nominal	Min/Max	Random
Output of Injectors 1 + 2 + 3	300	300	293
Output of Injector 4	300	294	306
Error re 1 + 2 + 3 vs 4	0	-2.0%	4.4%
Output of Injectors 1 + 2 + 3 + 5	900	912	881
Output of Injector 6	900	882	918
Error re 1 + 2 + 3 + 5 vs 6	0	-3.3%	4.2%

It may be seen that if it were simply assumed that all injectors were nominal, or "perfect" when the metering valve was increasing the flow from, for example, 900 SCFH to just over 900 SCFH, when the valve changed from using injectors 1 + 2 + 3 + 5 to using injector 6, there would possibly be an error in fuelling of

3-4%. This might not necessarily noticeably affect the performance of some engines, but for proper operation of, for example, three-way catalytic convertors, it is desirable to have the fuel supply controlled within 0.25%.

To compensate for such errors, one of the pulsing injectors may be used to bridge the gap between the two flow rates. The use of pulsing injectors further provides for greater definition of flow using a limited number of injectors. Clearly, the pulsing cannot be used to provide infinite flow definition, and to provide more accurate prediction of flow a minimum on-time is set for each injector, such that proper control of the valve is maintained and the less predictable pull-in and drop out flowrates have proportionally less effect on the total predicted flow. Typically, for the desired degree of control, a pulsing injector requires a minimum off time of 900,µs and has a pull in time of 1200,µs.

Downstream of the metering valve, the metered fuel is mixed with air before being supplied to the engine. 36 The fuel and air are conveniently mixed in or after the engine air cleaner. A fuel mixer 360 and a fuel nozzle 362 suitable for use in this environment is illustrated in Figures 8 and 9 of the drawings. Both the fuel mixer 360 and the fuel nozzle 362 are adapted for providing dispersion of the fuel in the air stream. In this system, the fuel is supplied from the metering valve at a positive pressure, preferably at a pressure of between 1 and 2 p.s.i.

Figure 8 illustrates a mixer 360 suitable for location in the intake air duct 364 between the air cleaner and throttle plate. The mixer 360 includes a right-angle nozzle inlet 366 for connection to a hose (not shown) leading from the metering valve outlet, the inlet 366 leading into a diffuser tube 368 provided with a series of openings 370 through which the fuel diffuses into the air being drawn into the engine. The ends of the diffuser tube extend through openings 372, 374 in the intake tube 364 and are located at one end by the nozzle inlet 366, and at the other end by a diffuser tube support 376. Sealing washers 378, 380 are located between the nozzle inlet 366 and tube support 376 and flats 382, 384 formed on the exterior of the intake air duct 364, while retaining nuts 386, 388 are provided on the interior of the duct 364 to hold the tube 368 in the nozzle inlet 366 and support 376.

The nozzle 362 illustrated in Figure 9 includes a simple diffuser cone 390 fitted to a right angle nozzle inlet 396 and is suited for fitting to an air cleaner, possibly in the air cleaner lid or the inlet snorkel. The illustrated example is shown fitted to an air cleaner lid 392, a sealing washer 394 being provided between the lid 392 and the inlet 396. The cone 390 provides a cone-shaped outlet which diffuses the fuel in the intake air.

When installed in the air-cleaner lid, a nozzle is located over each throttle bore.

The air cleaner lid is the preferred location on direct mounted air cleaners as a means to minimize transient delays and to minimize the volume of "stored" combustible charge above the throttles.

CONTROL OF METERING VALVE

To control the operation of the metering valve to provide the correct quantity of fuel to the engine requires the theoretical modelling of the fuel the calculated mass air flow through the engine. For sonic operation, the mass flow through the injectors of the metering valve has a linear dependency on absolute inlet pressure (assuming temperature constant). Thus the different fuel requirements of different size engines may be broadly accommodated by adjusting the metering valve inlet pressure, using the following equation to assure adequate flow capacity exists.

$$P_{(psig)} = K_R \left[\frac{P_p}{0.3 \; LHV \; \dot{m}_{max}} (70) + 30 \right] \quad (2)$$

K_R = constant depending on regulator characteristics

P_p = peak engine power [kW]

LHV = lower heating value of fuel [kJ/g]

$\dot{m}_{max}$ = maximum fuel flow capacity at 100 psig [g/s]

This adjustment is achieved by adjustment of the pressure regulator. As mentioned above, an engine's instantaneous fuel flowrates are calculated based on the mass air flow to the engine. The mass air flow (MAF) is calculated as follows:

$$MAF = \frac{K . n_{air} . D . RPM . MAP . (1-EGR) . \eta_{vol}}{(T_{mix})} \quad (3)$$

Required fuel flow: $m_{CNG} = MAF/\lambda$ (3a)

Where K = conversion constant

n_{air} = air portion of intake charge

D = engine displacement (litres)

RPM = engine speed (rev./min.)

MAP = manifold absolute pressure ("Hg)

η_{vol} = volumetric efficiency, function of MAP, RPM

T_{mix} = air charge obsolute temperature near intake valve (°K)

λ = mass air/fuel ratio

As can be seen above, equation (3) includes the volumetric efficiency (η_{vol}) as a function of MAP and RPM. One implementation of the control programme for the system includes a universal 208-point volumetric efficiency table (16 RPM cells X 13 MAP cells). An acceptable choice for the points are:

MAP : 29.6, 27.5, 25.6, 23.3, 21.2, 19.2, 17.5, 15.9, 14.5, 13.1, 11.7, 9.9, 7..4

RPM : I, $I(T/I)^{2/9}$,...$I(T/I)^{8/9}$, T, $T(P/T)^{1/2}$, $T(P/T)^{3/4}$, P, 1.15.P, $(1.15)^2$.P

where: P peak power RPM

T - peak torque RPM

I = idle RPM

Volumetric efficiency can be empirically determined on each engine. Alternatively, a mathematical model may be used to develop the volumetric efficiency of each engine. The overall volumetric efficiency is defined as the actual mass of fresh air which passes into an engine cylinder during one intake stroke divided by the ideal air mass (M_{air}) which would fill the piston displacement under the same conditions. for a 4-stroke engine:

$$\eta_{vol} = (2.MAP.60)/D.S.RPM) \quad (5)$$

a. for engine speeds > peak torque:

$$(RPM,MAP) = \eta\,peak \cdot \left[0.281 + \frac{\varepsilon - P_e/P_1}{1.39 \cdot (\varepsilon - 1)}\right]\left[1 - R \cdot \left(1 - \frac{RPM}{RPM_{p.T.}}\right)^2\right] (6)$$

b. for engine speeds ≤ 4 peak torque:

$$(RPM,MAP) = \eta\,peak \cdot \left[0.281 + \frac{\varepsilon - P_e/P_1}{1.39 \cdot (\varepsilon - 1)}\right]\left[1 - S \cdot \left(1 - \frac{RPM}{RPM_{p.T.}}\right)^2\right] (7)$$

with Pressure ratio

$$\frac{P_e}{P_1} = \frac{C}{MAP} \cdot \left[a_0 + a_1 \cdot \left(\frac{MAP}{MAP_{max}}\right) + a_2 \cdot \left(\frac{MAP}{MAP_{max}}\right)^2\right] \cdot \left[b_0 + b_1 \cdot \left(\frac{RPM}{RPM_{p.p.}}\right)\right.$$
$$\left. + b_2 \cdot \left(\frac{RPM}{RPM_{p.p.}}\right)^2\right]$$

where

$\eta\,peak$ = estimated peak volumetric efficiency

ε = compression ratio

$RPM_{P.T.}$ = engine speed at peak torque (rev./min.)

$R.P.M._{p.p.}$ = engine speed at peak torque (rev./min.)

$$R = \frac{(1 - C)}{\left(1 - \frac{RPM_{pp}}{RPM_{PT}}\right)^2}$$

$$C = \frac{\left(\frac{4000 \cdot T_p}{D} + FMEP_p\right)}{\left(\frac{4000 \cdot T_T}{D} + FMEP_T\right)}$$

$$FMEP = \left[c_0 + c_1 \cdot \frac{D \cdot RPM}{z \cdot b^2} + c_2 \cdot \left(\frac{D \cdot RPM}{z \cdot b^2}\right)^2\right]$$

$$S = \frac{(1 - \eta_i)}{\left(1 - \frac{RPM_i}{RPM_{PT}}\right)^2}$$

$$\eta_i = (1 - \eta_e)\left(\frac{RPM_{PT}}{RPM_i}\right)\left[1 - 15\left(\frac{1}{RPM_i} - \frac{1}{RPM_{pt}}\right)\right] \cdot \sqrt{\frac{T_c}{T_b}}$$

$a_0, a_1, a_2, b_0, b_1, b_2, c_0, c_1\ c_2$ = empirical constants

RPM_I = engine speed at idle (rev./min.)

η m = mechnical efficiency

T_c = thermostat opening temperature [K]

T_b = base temperature [K]

5   z = number of cylinders

b = cylinder bore [mm]

As the estimation of peak volumetric efficiency (ηpeak) for each engine is somewhat cumbersome and it has been found that ηpeak = .85 is a reasonable approximation for the majority of naturally aspirated spark ignition (S.I.) engines. However, the figure is typically higher when tuned intake or exhaust manifolds are

10 used, or when an engine is turbocharged or supercharged. Appropriate values must be calculated or approximated for these less common configurations.

As noted from egrnation (3), mass flow determination requires measurement of air temperature near the intake valve (T_{six}). For existing vehicles, the inconvenience of an aftermarket installation of a temperature sensor near the intake valve retires the prediction of the air charge temperature increase from the air

15 temperature sensor location, typically in the air cleaner to the intake valve.

The modelling of the mixture temperature $(T_{mix})^{\cdot}$ K near the intake valve involves calculation using calibrated and measured data:

$$20 \qquad T_{mix} = T_s - (T_s - (T_s - T_{ia})^{\cdot exp} \left\{ \frac{K_1 * Z^{0.6} * L}{(RPM_{pp} * D)^{0.4} * (MAF)^{0.2}} \right\} + T_{uni}$$

$$25 \qquad T_{ia} = \frac{1.007(A) \ (LAMBDA) \ (T_{air}) \ + \ 2.23(T_{fuel})}{1.007(A) \ (LAMBDA) \ + 2.23}$$

$$T_{uni} = \frac{K_2 . (RPM_{pp}) . (D)}{MAF} \quad \text{for unisided heads}$$

$$30 \qquad\qquad = 0 \quad \text{for crossflow heads or v-type manifolds}$$

T_{air} = air inlet temperature [K]

T_{fuel} = fuel temperature [K]

35   Z = # of cylinders   L = intake runner length [m]

RPM_{pp} = engine speed at peak power [RPM]

D = engine displacement [litre]

A = stoichiometric air/fuel ratio

LAMBDA = nominal excess air ratio; for real time metering

40   MAF = mass air flow [g/s] (calculated using equation (1) with $T_{mix} = T_{air}$)

$K_1 . K_2$ = empirically determined constants

Figure 10 is a block diagram of a suitable computer and sensor set up for controlling the metering valve to provide desired fuel flows, as described above, and illustrates the various sensors which are utilized to determine the settings of the metering valve.

45   The system power inputs 400 include an input from the battery and a ground line. The analog inputs 402 include engine data 404, fuel system data 406, miscellaneous data 408 and a number of spare lines for future requirements 410. The engine data 404 includes engine coolant temperature, intake-air temperature, intake manifold absolute pressure, and exhaust gas oxygen. The fuel system data includes fuel storage pressure (gauge), fuel regulated pressure (absolute) and fuel regulated temperature. The miscellaneous

50 inputs include barometric pressure, battery voltage and a reference voltage (5 volts dc).

The analog inputs are converted to digital signals for processing.

The digital inputs 412 relate primarily to status, and include inputs from the starter solenoid, gasoline mode select, natural gas or propane mode select, the exhaust gas recirculator (EGR), and ignition key.

Inputs 414 relating to engine speed are classified as high speed inputs, and comprise the coil negative,

55 that is the engine R.P.M., and possibly also an input relative to actual vehicle speed. In this particular example, for use in fitting to a conventional gasoline fuelled vehicle a number of high speed inputs may also be obtained by intercepting the original engine manufacturer's (OEMs) data lines 416, such as the top dead centre sensor, the knock sensor and exhaust gas oxygen sensor.

An input may also be provided from the vehicle dashboard fuel gauge.

Calibration inputs 418 are provided for communication with a synchronous serial port 419 for use in calibration of the sensors for detecting top dead centre, knock, exhaust gas oxygen and the dashboard fuel gauge.

5   The inputs are fed to the computing section 420 which includes an analogue to digital converter (for the analogue inputs), a clock, a microprocessor, an EPROM, bus drivers, and battery (for back-up power).

An output from the computing section 420 passes through an output buffer 422 to provide the reference voltage output 423.

Other outputs from the computing section pass through saturated 1 Amp drivers 424 to an EGR
10   override solenoid and an optional idle compensator outputs 425.

2 Amp drivers 426 are also provided for outputs 427 for control of a gasoline solenoid or relay, for twin-fuelled vehicles, the solenoid in the pressure regulator, and a coolant supply solenoid.

A plurality of metering valve data lines 428 are also provided, one line for each solenoid of the valve. For a typical natural gas application approximately seven or eight outputs 429 will be provided, and on
15   propane or LPG applications nine or ten injectors and outputs may be required. As mentioned above with reference to Figure 5d, due to the heat they produce, the hi-current foldback drivers are located in the metering valve body.

20   CLOSED LOOP SYSTEM

To further compensate for fuelling errors, an active oxygen sensor feedback system and a keep alive adapted memory are included in the control system.

Fuelling errors may be caused by various deviations, including:
25   - sensor deviation from the respective calibration curve
- inaccuracy of metering valve calibration curve
- deviation of actual vs. calculated volumetric efficiency
- deviation of actual vs. calculated air charge temperature near intake valve deviation of actual vs. calculated fuel demand
30   - changes in natural gas composition

In order to assist the oxygen sensor in quickly finding stoichiometry, an adaptive memory strategy is provided and structured in a similar manner to the volumetric efficiency table, that is, a table provided with cells, for example 16 RPM cells X 13 MAP cells, each cell holding a value for a volumetric efficiency correction matrix, VC (RPM, MAP).
35   Initially, the table holds values of VC = 1, and as the vehicle is operated within closed loop within a cell, the particular value of VC (RPM, MAP) is altered until stoichiometry is reached. The table holds the altered values and can thereafter reach stoichiometry more quickly, as the starting value is likely to be closer to the desired value.

As a further refinement, a series of separate VC (RPM, MAP) factors could be created and stored in the
40   computer's memory, to uniquely compensate for metering errors identified by the closed loop during readily identifiable distinct operating modes such as for EGR active, EGR inactive, air temperature within specific limits, barometric pressure within specific limits, rate of change of engine speed greater than a specific value, MAP value less than minimum standard point by more than a specific value, and the value in the standard matrix.
45   The above described embodiment has been described with reference to sonic flow through the orifices of the metering valve. It is also possible to operate the system using sub-sonic flow, though this complicates control as the outlet pressure in the metering valve must be taken into account in order to calculate the mass flow rate through each orifice. Sub-sonic flow may be considered in circumstances where the fuel, typically propane, will be operating at or below the critical pressure for the orifice geometry
50   used (that is, the sonic pressure ratio could not predictably be maintained across the orifice). In propane systems this would be most likely to occur at temperatures below -20°C where there was inadequate heat from the engine and/or environment to vaporize the fuel and maintain it at a sufficiently high pressure.

Reference has primarily been made to spark ignition engines, though the system may also have utility in conversion of compression ignition or diesel engines. Typically natural gas will not ignite due to
55   compression at compression ratios below 20:1, such that an ignition using either pilot injected diesel fuel, or a separate spark plug arrangement will be necessary. Nonetheless, the system described herein is viable for such applications.

Further, while the above described embodiments are adapted for use with internal combustion engines,

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it is of course possible that the system, and the components thereof, could be adapted for use in other applications.

5 Claims

1. An apparatus for controlling the rate of flow of a fluid from a common inlet to a common outlet, the apparatus including a plurality of fluid conducting lines having a plurality of flow capacities, said plurality of lines being connected in parallel between said common inlet and said common outlet such that the total flow 10from said common inlet to said common outlet is equal to the sum of the separate flows through the individual lines; a bi-stable fluid flow control valve located in each of said lines; sensors for measuring parameters of the fluid sufficient to determine the potential mass flow of said measured fluid through each control valve when open; control means adapted to control selectivelythe opening and closing of said control valves and monitor the sensors to determine the potential mass flow through each control valve in accordance with the measured 15fluid parameters, the total fluid flow passing outwardly of said common outlet comprising a base flow component established by opening selected control valves to provide a continuous predetermined flow, discrete step changes in the base flow component being provided by opening and closing combinations of control valves;
characterized in that:
20at least one of said control valves is a pulsing valve, and in that increments of fluid flow between said discrete steps are provided by opening at least one pulsing valve for a fraction of a predetermined time period to provide a desired average flow over said time period.

2. The apparatus of Claim 1, wherein the sum of the flowrates through the two lines having the lowest flow capacities is greater than the flowrate through the line having the third lowest flow capacity.

253. The apparatus of Claim 2, wherein the flowrate capacities of the two fluid conducting lines having the lowest flow capacities are substantially equal.

4. The apparatus of Claim 1, wherein there is one pulsing control valve located in the fluid conducting line having the lowest flow capacity.

5. The apparatus of Claim 1, wherein there are two pulsing control valves which may be opened for a fraction 30of said predetermined time period and which are located in the two fluid conducting lines having the lowest flow capacities.

6. The apparatus of Claim 1 further comprising a metering orifice in each of said fluid conducting lines, the pressure difference between the common inlet and the common outlet being maintained at a level sufficient to provide sonic flow through the orifices in each fluid conducting line.

357. The apparatus of Claim 6, wherein the control valves are electrically operated solenoid valves, the control means being adapted to apply a first current to the solenoids to open the respective valves and then apply a lower second current to hold the valve open.

8. The apparatus of Claim 1, wherein the fluid is fuel for an internal combustion engine and the control means operates the control valves to provide a supply of fuel in accordance with selected engine parameters, the 40engine operating on one of: spark ignition or compression ignition, said discrete time period being the time between combustion events.

9. The apparatus of Claim 8, wherein the control means is adapted to determine the required fuel flow of the engine based on various parameters, the required fuel flow being proportional to the volumetric efficiency of the engine as a function of engine manifold absolute pressure and engine speed, the control means including 45a look-up table containing a plurality of cells corresponding to preselected ranges of engine manifold absolute pressures and engine speeds.

10. The apparatus of Claim 9, and further including a pressurized fuel container and a fuel pressure regulator for supplying fuel from the pressurized fuel container at said first pressure to said common inlet, the metered supply of fuel being mixed with the intake air of the engine, a diffuser cone being provided in fluid 50communication with the common outlet and located in the engine air intake.

11. The apparatus of Claim 1, wherein the flow capacities of the two fluid conducting lines having the highest flow capacities are each substantially equal to twice the flow capacity of the next lowest flow capacity fluid conducting line.

12. The apparatus of Claim 1, wherein the flow capacities of the two fluid conducting lines having the highest 55flow capacities are each substantially equal to the sum of the flow capacities of the two next lowest capacity fluid conducting lines, one of said two next lowest capacity fluid conducting lines having a flow capacity twice that of the other fluid conducting line.

13. The apparatus of Claim 1, wherein said flow capacities of said fluid conducting lines are related to one

another as to be proportional to respective ones of a plurality of preselected numerical values, said preselected numerical values following the series 2^0, 2^0, 2^1, 2^2, ..., 2^{n-2} and 2^{n-1}, where there are n + 1 fluid conducting lines.

14. The apparatus of Claim 1, wherein said flow capacities of said fluid conducting lines are related to one another as to be proportional to respective ones of a plurality of preselected numerical values, said preselected numerical values following the series 2^0, 2^0, 2^1, 2^2, ..., 2^{n-2} and 2^{n-2}, where there are n + 1 fluid conducting lines.

15. The apparatus of Claim 1, wherein said flow capacities of said fluid conducting lines are related to one another as to be proportional to respective ones of a plurality of preselected numerical values, said preselected numerical values following the series 2^0, 2^0, 2^1, 2^2, ..., 2^{n-4} and 2^{n-3}, $(2^{n-4} + 2^{n-3})$ and $(2^{n-4} + 2^{n-2})$ where there are n + 1 fluid conducting lines.

16. A method for controlling the rate of flow of a compressible fluid between a common inlet at a first pressure and a common outlet at a lower second pressure through a plurality of parallel fluid conducting lines adapted to provide a plurality of flowrates therethrough, each conducting line being provided with a bi-stable fluid flow control valve, the method including controlling selectively the opening and closing of said control valves to control the fluid flow passing outwardly of said common outlet by providing a base flow component established by opening selected control valves to provide a continuous predetermined flow, discrete step changes in the base flow component being provided by opening and closing combinations of control valves; characterized in that:

at least one of said valves is a pulsing valve, and in that the method further includes providing increments of fluid flow between said discrete steps by opening at least one pulsing valve for a fraction of a predetermined time period to provide a desired average flow over said predetermined time period.

17. The method of Claim 16, wherein the compressible fluid is fuel for supply to an internal combustion engine and said predetermined time period is the time between combustion events.

18. The method of Claim 16, wherein the minimum open time of said pulsing valve for one predetermined time period is the time taken for the valve to open and the maximum open time of said valve for one predetermined time period is the predetermined time period less the time for the valve to close.

19. The method of Claim 16, further including determining the response time of individual control valves to open and close commands, determining the flow through the lines while the control valves are changing states, and timing the opening and closing of said control valves to provide said desired discrete step changes in said base flow component.

20. The method of Claim 17, further comprising mixing the metered fuel with the intake air of the engine by dispersing the fuel in the engine air intake through a diffuser cone.

21. A fluid metering device for use in a gaseous fuel injection system for an internal combustion engine comprising:

(a) a body defining an inlet fluid manifold and a metered fluid manifold;

(b) a fluid inlet for introducing fluid into the inlet fluid manifold;

(c) a plurality of bi-stable fluid flow control valves for communication between the inlet fluid manifold and the metered fluid manifold;

(d) valve actuators for opening and closing the valves;

(e) a fluid outlet for the passage of metered fluid from the metered fluid manifold; characterized in that:

(f) sensors are provided in communication with the inlet fluid manifold to determine parameters of the inlet fluid and the metered fluid sufficient to determine the potential mass flow of fluid through each of the valves; and

(g) valve control means are provided for activating the valve actuators to open the valves in combinations and for time intervals to give a desired total mass flow of fluid through the valves.

22. The fluid metering device of Claim 21, wherein the valve actuators are solenoids and each valve includes an orifice and a movable plunger for closing the orifice, and wherein, to open a valve, the coil of each respective solenoid is initially supplied with a first current to retract the plunger and the current supply to the coil is then decreased to a second lower current to maintain the plunger in the retracted position.

23. The fluid metering device of Claim 22, wherein an inlet chamber defining a fluid reservoir is provided surrounding each orifice to minimize the lag time for fluid to start flowing through the orifice when the valve is initially opened.

24. The fluid metering device of Claim 22, wherein heating means are provided for heating the body to compensate, in part at least, for the cooling of the fluid which takes place on expansion of the fluid passing through the valve orifices.

25. The fluid metering device of Claim 24, wherein the fluid metering device forms part of a system for controlling the flow of fuel to an internal combustion engine including a liquid cooling system, the heating

means deriving heat from the liquid cooling system of the engine.

26. The fluid metering device of Claim 22, wherein each valve activating solenoid is linked to a current controller, the current controllers being mounted to the body of the device, each current controller being operable to provide a first current to a respective solenoid to open the valve, followed by a lower second
5 current to hold the valve open.

27. A pressure regulator for reducing the pressure of a fluid supplied at a first pressure to a lower second pressure comprising:

(a) a body defining an inlet fluid chamber and a regulated fluid chamber;

(b) a fluid inlet for passage of high pressure fluid at a first pressure into the inlet fluid chamber;

10 (c) a single stage regulating valve for fluid communication between the inlet fluid chamber and the regulated fluid chamber and arranged to prodtlce a drop in pressure in the fluid passing through the valve to a predetermined second pressure;

characterized in that,

the regulator further comprises

15 (d) a relief valve in fluid communication with the regulated fluid chamber and arranged to open to exhaust fluid when the pressure in the regulated fluid chamber rises above a predetermined level;

(e) heating means adapted for heating the body; and

(f) a fluid outlet in fluid communication with the regulated fluid chamber for passage of regulated fluid from the regulated fluid chamber.

20 28. The pressure regulator of Claim 27, wherein a shut-off valve is provided between the fluid inlet and the inlet fluid chamber, the shut-off valve comprising a high-pressure solenoid, a pilot piston and a primary piston, the primary piston being adapted to close a valve orifice.

29. The pressure regulator of Claim 28, wherein the primary and pilot pistons are located in a solenoid tube, each piston having a proximal and distal end, the proximal end of the primary piston extending from the tube
25 and, with the valve in the closed configuration, closing the valve orifice, the primary piston having a first fluid communicating passage extending from the proximal end to a passage opening at the distal end of the piston and being in fluid communication with the valve orifice of the proximal end, the proximal end of the pilot piston closing the passage opening, a fluid communicating passage being provided between the fluid inlet and a space in the solenoid tube defined by the distal end of the primary piston and the proximal end of the pilot
30 piston, to open the valve, the solenoid coil being energized to retract the pilot piston, the first pressure acting on the primary piston initially preventing retraction of the primary piston by the solenoid coil, fluid then passing from the inlet through the second fluid communicating passage between the fluid inlet and the space between the pistons, the first fluid communicating passage extending through the primary piston, and the valve orifice into the inlet chamber, until the pressure in the inlet chamber rises sufficiently to permit retraction of the
35 primary piston by the solenoid coil.

30. The pressure regulator of Claim 29, wherein the second fluid communicating passage between the fluid inlet and the space between the pistons is formed of channels provided in the surface of the primary piston.

31. The pressure regulator of Claim 27, wherein the regulating valve is in the form of a poppet valve.

32. The pressure regulator of Claim 27, wherein the relief valve is arranged to open to exhaust fluid through a
40 relief outlet, the valve comprising a first chamber in communication with the regulated fluid chamber and opening into a second chamber in communication with the relief outlet, the opening between the chambers normally being closed by the head of a relief piston biased to close the opening.

33. A method of mixing a metered supply of compressible fluid fuel with the intake air of an internal combustion engine, characterized in that a source of metered fuel is provided at a positive pressure, and the
45 fuel is dispersed into the air intake of the engine through a diffuser cone.

34. A method of mixing a metered supply of compressible fluid fuel with the intake air of an internal combustion engine, characterized in that a source of metered fuel is provided at a positive pressure, and the fuel is dispersed in the air intake of the engine.

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FIG. 1

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FIG. 2

FIG.3a

216 162 166 168 42 44 16

3a 3d 3d 3a

3e 3e 212 34 210

214 211

FIG. 3b

14

162
176
179
174 183

177
36 181

FIG. 3c

FIG. 3d

FIG. 3e

FIG. 4

FIG. 5a

FIG. 5b

FIG. 5c

FIG. 5d

FIG. 6

FIG. 7a

FIG. 7b

464

454

456   460

462

17

450

FIG. 7c

17

314   336   312

338

466

348

350

FIG. 7d

FIG. 8

FIG. 9

FIG. 10